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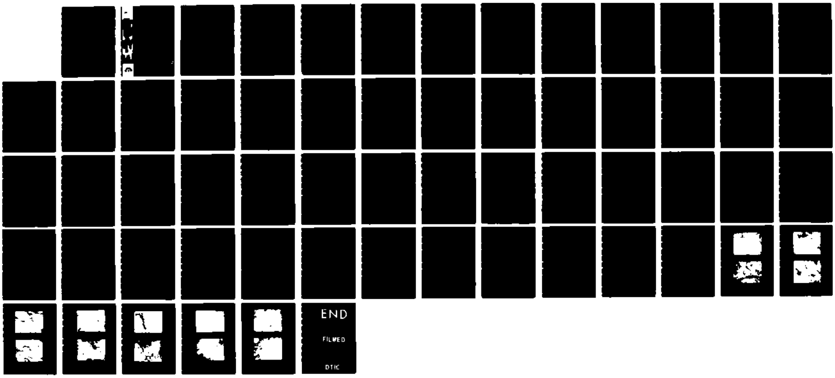

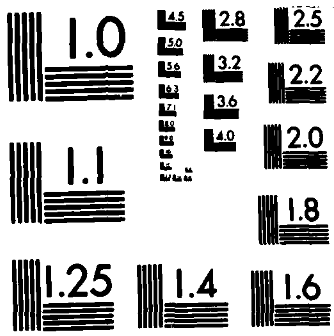

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DEVELOPMENT OF TWO CANDIDATE CONCRETE MIXTURES (SALT, NONSALT) FOR REPOSITORY SEALING APPLICATIONS

by

Alan D. Buck

Structures Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

August 1985

Final Report

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<tr><td colspan="3">20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Two concrete mixtures were developed in 1983 for possible use in repository sealing application. The salt concrete was basically an adaptation of BCT 1-F salt grout made by adding aggregate. The nonsalt mixture was a similar adaptation of nonsalt BCT 1-FF grout.
The basic requirement was continued workability after 2 hr of intermittent mixing. Tests of hardened specimens included strength, modulus of elasticity(E),
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20. ABSTRACT (Continued).

permeability, coefficient of linear thermal expansion, thermal conductivity, expansion, creep, and examinations by X-ray diffraction for phase composition and by scanning electron microscopy for microstructure. Some of the physical tests were done on specimens that had been kept at 23 $\pm$ 1.7° C and on other specimens kept at 61 $\pm$ 2° C. Tests for expansion and examinations for phase composition and microstructure are being continued at 6-month or yearly intervals.

It was concluded that each concrete mixture was a viable candidate for use in repository sealing applications.

Preface

This report was prepared for the US Department of Energy (DOE) under continuing contract DE-AI97-81ET 46633. It was a milestone item for FY 84 and was prepared as a draft report in September 1984. The draft report has been revised to include additional data for publication as a Miscellaneous Paper. Mr. Steve Webster of the DOE in Columbus, Ohio, was Project Manager for this study.

This report was prepared in the Concrete Technology Division (CTD) of the Structures Laboratory (SL) of the USAE Waterways Experiment Station (WES) by Mr. Alan D. Buck under the direction of Mr. J. M. Scanlon, Chief, CTD, and Mr. B. Mather, Chief, SL; Mr. Buck was Project Leader in the CTD.

COL Robert C. Lee, CE, was Commander and Director of WES during the conduct of this study and the preparation of this report. COL Allen F. Grum, USA, was Director of WES during publication. Mr. Fred R. Brown and Dr. Robert W. Whalin were Technical Directors.

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Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

DEVELOPMENT OF TWO CANDIDATE CONCRETE MIXTURES (SALT, NONSALT) FOR REPOSITORY SEALING APPLICATIONS

Background

1. At a planning meeting held at the USAE Waterways Experiment Station (WES) in November 1982, it was directed that during FY 83 work would be done on the design and evaluation of concrete mixtures rather than grout mixtures. It was specifically agreed that WES would use local aggregates with BCT-1-FF and BCT-1-F grouts, modified as necessary, to make a salt-free and a salt-bearing concrete mixture, respectively. Specimens would be cast from these mixtures and tested at a variety of ages. An important stipulation was that each mixture should remain workable for several hours and be nonshrinking.

2. The material in this report is a description of the proportioning, casting, and testing of those two mixtures.

Revisions

3. An interim report was issued in September 1983 covering development of two concrete mixtures plus casting and testing of specimens through about 90 days of testing. The present report was prepared in September 1984 as a revision of the September 1983 draft, so as to include data through 1 yr or more of testing. Specific additions or changes include the following:

a. Tables 7 and 8 were revised to include strength data at 180- and 365-day ages.

b. Tables 12, 13, 14, and 15 presented length-change data for restrained and unrestrained bars from both concrete mixtures at two temperatures. Since all of the bars kept at 61 ± 2^{o} C showed continuous shrinkage, it was obvious that sealing had been ineffective. These heated bars from the nonsalt mixture were unwrapped and placed in a moist environment at room temperature for about 200 days with periodic measurement. The four tables were revised to show these changes and additional expansion data for the bars continuously stored in a moist environment. The following tabulation shows the 12 sets of bars that were originally tested, not all were shown in the four tables, and their present status:

Nonsalt Concrete

(1) Restrained bars R1 through R3 are still being tested at 6-month intervals (Table 12).

(2) Heated restrained bars R4 through R6; testing discontinued after about 1 yr (Table 12).

(3) Unrestrained bars U1 through U3 are still being tested at 6-month intervals (Table 13).

(4) Heated unrestrained bars U4 and U5; testing stopped after about 1 yr (Table 13).

(5) Bars 67, 69, and GOLU were made using gypsum instead of plaster of Paris; testing stopped after 1 yr.

(6) Testing of bars from developmental Trial Mixture 3 was stopped after 7 days.

Salt Concrete

(1) Restrained bars R1-2 through R3-2; testing stopped after 153 days (Table 14).

(2) Heated restrained bars R4-2 through R6-2; testing stopped after 90 days (Table 14).

(3) Unrestrained bars U1-2 through U3-2; still being tested at 6-months intervals (Table 15).

(4) Heated unrestrained bars U4-2 through U6-2; testing was stopped after about 90 days (Table 15).

(5) Bars 20, 30, and 59 made with melamine-based high-range water reducer (HRWR) instead of naphthalene-based HRWR; testing was stopped after 180 days.

(6) The testing of bars from developmental Trial Mixture 5 was stopped after 7 days.

c. The results of testing specimens from both concrete mixtures for creep through 1 yr are presented.

d. The results of work to monitor phase composition and microstructure of the cement paste portion of each concrete mixture are presented. Since the decision to do this work was not made until specimens from the original concrete mixtures were over 90 days old, it was necessary to remake small batches of each concrete to obtain early-age data; these batches were made on 24 May 1984. Since the early-age data for these mixtures were to correlate with the mixtures made in 1983, no changes in materials were made. This meant that the salt mixture had an excessive air content. Compressive strength data through 90 days were determined for the repeat mixtures for comparison with data from the original batches of concrete (supplemental Tables 7A, 8A). Phase composition was determined by examination of cement paste concentrations, obtained from spares or from broken cylinders, by X-ray diffraction (XRD) in sealed environments to minimize the likelihood of phase changes; this was done at 7-, 28-, and 97-day ages and at the 13-month ages. All XRD patterns were made with an X-ray diffractometer using nickel-filtered copper radiation. Microstructure of the two concretes was studied by scanning electron microscopy (SEM) using broken surfaces of small pieces of extra cylinders of the two concretes. These specimens were vacuum dried and broken surfaces

were then coated with a layer of carbon (approximately 50 A) and a layer of gold-palladium alloy (approximately 150 A) before examination. These examinations were made at 7- and 97-day ages and again at 13 months. No SEM examination was made at 28 days.

e. The work done by Dr. C. Pace in 1983 to monitor the stress developed by the concrete mixtures in steel pipes failed to show the expansion levels indicated by length-change testing of the concrete bars already mentioned. Therefore, this work was partially repeated using the more expansive salt concrete mixture and the much more expansive sanded modification of salt grout BCT-1-F (same as TT83) (Buck 1984). These two mixtures were made 5 September 1984, so test data are limited; these will be covered in a separate report by Dr. Pace which will be prepared during FY 85. Nine bars were made from each mixture and are being monitored for expansion in a moist environment at about 73° F. These data are presented in this report and will also be in Dr. Pace's report. The salt concrete mixture was modified slightly to take advantage of earlier experience or because of material shortages. Three of these changes, shown below, are not considered significant, but the first one is significant because of its effect on air content.

(1) A melamine HRWR was used to avoid generation of an excessive air content.

(2) Since extended workability had already been demonstrated, the new batch was intermittently mixed for 30 min rather than 2 hr.

(3) A different local gravel was used.

(4) The De-Air chemical admixture was used even though it was no longer considered necessary.

Materials

4. The following materials were used to make the concrete mixtures:

a. Class H cement from the Maryneal Plant of Lone Star Industries at Sweetwater, Texas. The second, third, and fourth shipments of RC-836 from this plant were blended to obtain adequate material; designated RC-836(2-4).

b. Fly ash AD-592(2). This ash is from the Harrington Plant of Southwest Public Service in Amarillo, Texas. It was obtained at Artesia, New Mexico, under the trade name "Litepoz III."

c. Plaster. A commercial plaster was used; it consisted of calcium sulfate hemihydrate.

d. A commerical HRWR ("superplasticizer"), designated AD-627, was used.

e. A commercial dry defoamer, AD-678, was used with the salt mixture to inhibit foaming and subsequent entrapment of air. It was used

instead of the liquid AD-599 that had been used with BCT-1-F and 1-FF grouts because it was more effective with the concrete.

f. A commercial salt (NaCl) was used in the salt-bearing concrete mixture.

All of the above materials are the same as or equivalent to those used in grouts BCT-1-F and BCT-1-FF.

g. Coarse aggregate (32-90) CL-43 G-2. Two tons of No. 7 chert gravel were received 28 February 1983 from Lewis Miller Construction Co., Vicksburg, Mississippi. This material is from their pit near Highway 80-E a few miles beyond the intersection of Highways 80 and 27.

h. Fine aggregate (32-90) CL-43 S-1. Twelve tons of natural sand were received 18 February 1983 from Magnolia Ready-Mix Co. It is from the Runyon pit off Highway 27-S a few miles beyond the same intersection as above.

Two drums of this gravel and two drums of this sand were shipped to the Materials Research Laboratory of the Pennsylvania State University (PSU) on 17 March 1983 so they would have the same aggregate materials in mixtures they might make. The gravel and the sand were given the usual basic physical tests used for aggregates. Since they were from sources previously tested or believed to be similar to other nearby tested sources, no other tests were made.

5. XRD was used to check cement, fly ash, and plaster as needed to verify that no significant changes had occurred during storage. These and the other materials had already been given routine chemical and physical tests as part of earlier work. The cement was analyzed after blending the three shipments and its head of hydration was determined at 3, 7, and 28 days at ambient temperature and at 60° C.

Mixtures

6. The salt-free concrete mixture was developed first. First efforts to combine the BCT-1-FF grout with aggregate produced a concrete mixture with too much slump. The third trial mixture with more aggregate and less cement, fly ash, and plaster had 10+ in. of slump after initial mixing; slump was then 9-1/4 in. after 1 hr and 4-3/4 in. after 2 hr of mixing 5 min out of every 30 min. Three restrained expansion bars, each 3 by 3 by 10 in., had an average expansion of +0.02 percent at 7 days; this much expansion was considered minimally satisfactory. Experimental work with more plaster in just the mortar fraction showed substantially more expansion of smaller unrestrained bars.

However, when more plaster was tried in the concrete mixture, there was set within the first 30 min after mixing. Additional experimentation with the mortar fraction indicated the plaster could be retarded for 3 hr by use of a common plaster retarder. Efforts to duplicate this effect with concrete were not successful because the consistency was too stiff even though slump was maintained.

7. In order to meet an impending milestone deadline, it was decided to use the earlier trial mixture No. 3 which had good workability and only slight expansion. This mixture was made in two batches on 18 April 1983. Two batches were made because the volume needed would overtax the 16-cu ft mixer that was used. The first 14-cu ft batch had an initial slump of 11 in. When this unexpectedly dropped to 7-1/4 in. after 30 min, 10 lb of water were added without effect because the slump was still too little (6-1/2 in.) at 1 hr. At that point 3.9 lb of the HRWR was added. This increased the HRWR content from 1.1 percent (weight of HRWR divided by combined weights of cement, ash, and plaster) to 1.9 percent and caused the slump to increase to 10 in. and it was still 10 in. at 2 hr. Since the concrete did not tend to segregate even though it was well above the desired 4 to 6 in. of slump at that point, it was used to cast specimens to avoid wasting the limited amount of materials that were available.

8. A second batch of 6 cu ft was then made and dosed with extra water and HRWR in the same proportions and at the same times as with the 14-cu ft batch. It was considered more important to match batches than to reduce slump at this time; specimens were made.

9. Scaling up of a concrete mixture from about 0.1 or 0.5 to 14 cu ft led to an unexpected slump loss which was overcorrected in these two batches. For future batches it would be recommended to increase the HRWR from 1.1 percent to 1.5 percent, leave the water unchanged, and adjust slump with time, if needed, with additional HRWR.

10. The following was done to compare the effects of using gypsum instead of plaster to obtain expansion. A small trial batch was made using gypsum instead of plaster. It was monitored for workability as earlier trials had been and three bars were made and monitored for restrained expansion.

11. There were difficulties in developing a mixture containing salt. The trial batches were very similar to the previous mixture with the addition of salt. Extended workability was no problem but the known foaming effect of salt (Hughes) led to excessive air contents. These tended to start at about 10 percent

after initial mixing and increase to about 20 percent during 2 hr of intermittent mixing. Earlier experimentation with salt grouts had shown the need for a defoamer to minimize entrapment of air, but this was not as effective with this concrete mixture. Since this increase in air with mixing time could not be prevented using these materials, it was minimized by dropping the requirement of mixing periodically for 2 hr and using an air-detraining agent to keep the air as low as possible. In the field one would do this by dry batching ingredients and waiting until the last possible moment to add the water. On 19 May 1983, 15-cu ft and 5-cu ft batches were made by mixing each batch for 3 min. Specimens were cast immediately. The larger batch had a slump of 9-1/4 in. and an air content of 11.8 percent; the smaller batch had the same slump and 6.8 percent air.

12. After the full mixture had been cast and specimens made, it was learned from Dr. M. Grutzeck of PSU* that he had just found by experimentation that a melamine-based HRWR was more effective than one based on naphthalene (AD-627) in preventing foaming of mortar mixtures. As a check on this with concrete, a small batch of concrete was made using a melamine-based HRWR in place of the AD-627 naphthalene one. It was monitored for air content and bars were made and measured for restrained expansion. It was significantly better for minimizing air content.

Specimens and Tests

Nonsalt concrete

13. The following specimens were made from the 14-cu ft batch of concrete:

Specimen Identification	Description Nominal Dimensions
1	4.5- by 26-in. pipe
2	6- by 36-in. pipe
3	8.6- by 26-in. pipe
4	14.2- by 27-1/2-in. pipe
5	18.1- by 56-in. pipe

These instrumented pipes were used to determine stress levels; each pipe was sealed immediately after filling to prevent any evaporation.

* Personal communication.

R1 through R7 and U1 through U7	Seven restrained and seven unrestrained 3- by 3- by 10-in. bars. After 24 hr, one restrained (R7) and one unrestrained (U7) bar were placed in a device to continuously record length changes. The other bars were divided into restrained and unrestrained at 24 hr and half of each kind was kept in moist storage or sealed and placed in 61 $\pm$ 2° C storage. One bar (U6) had loose inserts and was not used.
1	Balloon for early volume change determinations.
CL-43* CON (1 through 20)	3- by 6-in. cylinders for strength and permeability tests. Half were sealed and heated at 61 $\pm$ 2° C.

Since there was not enough concrete to completely fill the largest pipe, approximately 1-1/2 cu ft of the second batch was used to complete filling it; this was done soon enough that no set had occurred.

14. The following specimens were made from the 6-cu ft batch of concrete:

Specimen Identification	Description
CL-43* CON-(21-24)	Four 6- by 12-in. cylinders for compressive strength and modulus of elasticity. Stripped at 24 hr with two then sealed and kept at 61 $\pm$ 2° C while the other two were kept in fog room. Tested at 7 and 28 days.
CL-43* CON-25	6- by 12-in. cylinder for permeability testing at 28 days.
CL-43* CON-(26, 27)	Two instrumented 6- by 12-in. cylinders to be tested for thermal conductivity at 28 days.
CL-43* CON-(28-31)	Four 6- by 16-in. instrumented cylinders to be tested for creep at 28 days.
CL-43 CON-(32, 33)	Two 6- by 16-in. instrumented cylinders to be tested for coefficient of linear thermal expansion at 28 days.
CL-43* CON-(34-53)	Twenty 3- by 6-in. cylinders for strength and permeability tests. Half were sealed and heated at 61 $\pm$ 2° C.
CL-43* CON-(54-56)	Three 3- by 20-in. in cardboard cylinder molds.

15. The only testing of hardened concrete that was common to both batches of concrete is the strength tests of 3- by 6-in. cylinders and the permeability

* Original serial numbers were recorded as CL-39 CON; later corrected to CL-43 CON.

testing of 3- by 6-in. cylinders CL-43 CON-4 and 37. The unhardened concrete was tested repeatedly for slump. Initial and final time of setting was determined for the large batch but only time of initial setting was done for the small batch.

Salt concrete

16. Batch sizes were 15 and 5 cu ft. Since it required longer to harden, no specimens were stripped until they were at least 48 hr old. An S was usually added after the serial number to denote salt. Since the same specimens were made as before plus more extras, they are described in less detail below:

Specimen Identification	Description
6-10	Largest to smallest pipes
R1-2 through R7-2 and U1-2 through U7-2	Fourteen 3- by 3- by 10-in. expansion bars
1	Balloon for early expansion
CL-43 CON-(1(S) through 25 (S))	3- by 6-in. cylinders
CL-43 CON-(26(S) through 28(S))	Extra 3- by 20-in. cylinders in cardboard molds
CL-43 CON-(29(S) through 33(S))	6- by 12-in. cylinders

All of the above samples including the time of set sample were made from the 15-cu ft batch. The remainder of them were made from the 5-cu ft batch.

Specimen Identification	Description
CL-43 CON-(34(S) through 37(S))	Instrumented 6- by 12-in. cylinders for modulus of elasticity and compressive strength
CL-43 CON-(38(S), 39(S))	Instrumented 6- by 12-in. cylinders for thermal conductivity
CL-43 CON-(40(S) through 43(S))	Instrumented 6- by 16-in. cylinders for creep
CL-43 CON-(44(S), 45(S))	Instrumented 6- by 16-in. cylinders for coefficient of linear thermal expansion
CL-43 CON-46(S) through 70(S))	3- by 6-in. cylinders
CL-43 CON-(71(S) through 73(S))	Extra 3- by 20-in. cylinders in cardboard molds
CL-43 CON-(74(S) through 77(S))	Extra 6- by 12-in. cylinders

Results

17. Most of the developmental and subsequent test data are shown in Tables 1 through 18. The test methods used were usually those described in the Corps Handbook for Concrete and Cement (Corps of Engineers 1949). Creep data are included (Figures 1 through 6). Detailed data for the pipe tests will be provided in a separate report.

18. Table 1 includes chemical and physical data for the Class H cement RC-836(2-4). As indicated earlier, shipments 2, 3, and 4 were blended to assure an adequate supply of cement. Comparison of data for Al_2O_3, SO_3, and surface area indicated that good blending was obtained. The heat of hydration of the cement at two temperatures and three ages is shown there as averages of duplicate determinations. These are based on the following individual values:

Age, days	23° C	60° C
3	60.2, 63.4	73.6, 74.9
7	67.2, 68.4	72.8, 75.0
28	76.9, 80.0	80.2, 82.0

19. Tables 2 and 3 show grading, absorption, and density (specific gravity) for the gravel and sand used, respectively. The data are in the usual range for these materials.

20. Data for the other materials were not determined since they were generally known but not always published. An earlier analysis of a later shipment of fly ash AD-592(4) was published (Roy, Grutzeck, Mather, Buck 1982).

21. Table 4 shows weights of materials needed to make 1 cu yd of the nonsalt mixture and other data. While air content was not checked, it would be expected to be between 1 and 2 percent since the mixture was not air entrained. A footnote to the table tells how to get the desired slump by reducing water so the water to cementitious solids ratio is 0.30. Start with the HRWR to cement plus fly ash plus plaster ratio adjusted to 1.5 percent by weight, and increase the latter during the 2-hr period if needed. This revision of what was actually done is needed because of what happened when the small trial batch was scaled up to a 14-cu ft batch. The slump unexpectedly dropped when the mixture was 30 min old and water and later HRWR were added to restore slump. The water was ineffective and the HRWR overcompensated because slump was still 10 in. at 2 hr.

The suggested revision should result in the desired slump of 4 to 6 in. 2 hr after initial mixing. While the table shows the ratio of water to cementitious solids, it would be more technically correct to show this as water plus HRWR to cementitious solids. This would have the effect of raising the ratio 0.01 when rounded. Since minor adjustments are usually needed anyway when putting a mixture together, this refinement was not shown in the table. This concrete mixture is basically the BCT-1-FF grout with coarse and fine aggregate added to make a concrete mixture. This particular grout is well known (Rhoderick, Wong, and Buck 1981). As stated earlier, the only opportunity to be identical is in the strength data (Table 7) and permeability of specimens CL-43 CON-4 and 37 (Table 9). Both of these comparisons indicate the two batches were essentially the same.

22. Table 5 contains mixture proportions and other data for the salt concrete mixture. It is much like the other concrete mixture with the addition of enough salt to the water to give 37.1 plus percent by weight of water (BWOW). As described earlier, trial mixtures showed high air contents after initial mixing (approximately 5 to 10 percent) that increased to 20 or more percent after 2 hr of intermittent mixing. For this reason specimens were cast immediately after 3 min of initial mixing to keep the air content as low as possible. Even so, air contents were 11.8 percent for the 15-cu ft batch and 6.8 percent for the 5-cu ft batch. In addition to the 11.8 percent being higher than desired, the two values were farther apart than desired. It was anticipated that this much difference would cause the higher air content concrete to be about 25 percent weaker. This was indeed the case and was the basis for not averaging the strength results for the different batches in Table 8. When it was learned that Dr. Grutzeck* of PSU had found that use of a melamine-based HRWR instead of a naphthalene-based one resulted in much less air in mortar mixtures, a 1-cu ft trial batch of concrete like the full casting but with this substitution was made. Intermittent mixing and periodic monitoring of slump and air content over 2 hr showed the following results:

Age, hr	Slump, in.	Air, %
Initial	9	3.0
1	7-3/4	2.3
2	7	2.1

* Personal communication.

While the slump was high, the lack of foaming and subsequent air content was a great improvement. On this basis, the salt mixture in the future should contain a melamine-based rather than a naphthalene-based HRWR and be modified slightly to reduce slump. Another small batch of this concrete with the melamine-based HRWR was made later and three restrained expansion bars were made for test and comparison with the Table 5 casting; the results will be discussed later with the other expansion data. The effect of salt was to increase times of setting by about a factor of two (Tables 4, 5).

23. Modulus of elasticity and compressive strength data for 6- by 12-in. cylinders at 7 and 28 days are shown in Table 6. The comparisons include age, the two types of concrete, and temperature. As expected, there is some increase of both properties with the increased ages and elevated temperature. Modulus and strength are both significantly lower for the salt concrete; part of this difference but probably not all of it would be due to the higher air content of the salt concrete and its slower hardening* which should have most effect on the 7-day results. The strengths are usually similar to those for 3- by 6-in. cylinders shown in Tables 7 and 8.

24. Table 7 shows compressive and tensile strength data of 3- by 6-in. cylinders from the two batches of nonsalt concrete stored at two temperatures through 1 yr. The data for the two batches were averaged since they were similar enough to believe they represented the same concrete. The average 1-day compressive strength was 2460 psi; tensile strength was not determined at 1 day. This mixture has an average compressive strength above 10,000 psi at 91-days age with tensile strength of 1,300 psi for specimens stored at room temperature. Corresponding strengths for heated specimens were 11,640 psi and 1,490 psi at the 91-days age. Final compressive strengths at 1 yr were about 13,000 psi with tensile strengths above 1,300 psi. Table 7A shows compressive strength values through 90 days for the batch made 24 May 1984 to study phase composition and microstructure. These data are similar to those for the same ages in Table 7, as they should be.

25. Similar strength data for the salt concrete are shown in Table 8. Due to longer hardening time and the weekend break, the earliest test was at 4 days; compressive strengths were 1840 and 2380 psi. As indicated earlier and as shown by the results in Table 8, the two batches of salt concrete

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* Slower hardening normally causes increased strengths at all ages beginning a few days after setting.

differed enough in air content that they were different. Therefore, the strength data were not averaged. The lower strengths of the salt concrete mentioned in discussion of Table 6 data are also evident here as 90-day values are 2920 and 3290 for compressive strength and 400 and 460 for tensile strength for specimens cured at room temperature. Specimens cured at about 60° C were correspondingly stronger. Compressive strengths at 1 yr were above 3000 psi for moist-cured specimens and above 5000 psi for heated ones. Tensile strengths were above 500 psi. Table 8A provides compressive strength data through 90 days for the small batch of concrete made 24 May 1984 for phase composition and microstructural study.

26. Liquid permeability results for nonsalt and salt concrete are shown in Table 9. The intent was to test at about their 28-days age. Two types of apparatus were used so results could be compared since driving pressure was 200 psi for both. The 6- by 12-in. cylinders were cut into 6- by 6-in. cylinders for testing the usual way by CRD-C 48-73.[2] The 3- by 6-in. cylinders were tested in a Hassler cell; there is no specified test method for this procedure at this time. The usual situation with the larger specimens is that they require about a day to encapsulate and there are often failures due to leaking through or around the alternate encapsulation materials of plaster, tar, and wax. Once a specimen leaks water or brine because of this, it is not practical to test it. This problem is reflected in the table where it is indicated that half of each larger cylinder leaked. Testing with a Hassler cell is preferable since there is no encapsulation to fail as a confining pressure is applied instead of encapsulation; in addition, testing can start immediately. There was a lack of such cells so only one salt concrete specimen was tested. Regardless of the testing difficulties, the nonsalt concrete was shown to have no measureable permeability by either method. The salt concrete was reported to have low permeability ranging from 0.01 to 1.1 microdarcy; the wide range between these two values is probably not significant at these low levels.

27. The coefficients of thermal expansion for both concretes are shown in Table 10. These average 7.24 millionths per deg F for the nonsalt concrete and 7.00 millionths per deg F for the salt concrete. The inclusion of salt in the concrete had very little effect on this property.

28. Table 11 shows the other thermal data that were measured. The average thermal conductivity in Btu per sq ft per hr per deg F per ft was 1.422 for the nonsalt concrete and 1.201 for the salt concrete. While this is

significantly more difference than shown by the coefficient of linear thermal expansion data, it is probably larger due to the higher air content and thus lower density of the salt concrete rather than to the salt itself.

29. Restrained and unrestrained expansion data for the nonsalt concrete stored at two temperatures are shown in Tables 12 and 13, respectively, through 1 to 2 yr of testing. The data for the elevated temperature all show shrinkage and are of no value. Since it is known from unpublished work that moist stored combinations of cement and plaster with or without the presence of a mineral admixture can show expansion at temperatures as high as 75° C, it is believed that all of the bars dried during the heating. It was more difficult to seal them than it was to seal the small cylinders. The heated bars were transferred to a moist environment for storage and periodic readings where they showed slight expansions through 211 days once they had an opportunity to gain moisture; all of these five heated bars (R4, R5, R6, U4, U5) were discarded. Expansion of bars stored at room temperature averaged 0.045 percent for restrained bars and 0.072 percent for unrestrained bars through 1 yr. Testing of these six bars (R1, R2, R3, U1, U2, U3) will continue at 6-month intervals. Overall, the nonsalt concrete is still showing slight but positive expansion through 2 yr of testing. The average restrained expansion of Trial Mixture 3 stored at room temperature ranged from 0.005 percent at 1 day to 0.021 percent at 6 days when measurements were stopped. The large batches were expanded versions of Trial Mixture 3. Limited experimental work had encountered difficulties with premature set and consistency when using more plaster or retarded plaster. A trial mixture was made using gypsum instead of plaster in an amount to furnish the same amount of sulfate. Restrained expansion bars cured at room temperature show average expansions of 0.004 percent at 1 day to 0.040 percent at 90 days so they are almost identical to corresponding data in Table 12. More experimental work would need to be done to determine if more expansion could be obtained with more gypsum in place of plaster without causing premature setting difficulties.

30. Tables 14 and 15 show expansion data for the salt concrete arranged as in Tables 12 and 13. As before, heating destroyed expansion. Room temperature expansions were significantly higher than those for nonsalt concrete. For example, the nonsalt concrete restrained expansion was 0.040 percent at 92 days while it was 0.071 percent for the salt concrete. The salt concrete was based on Trial Mixture 5 which gave 0.013 and 0.028 percent restrained expansions at

2 and 6 days, respectively. A final comparison is with salt concrete containing a melamine-based HRWR instead of the naphthalene-based one used in the large batches. The average restrained expansion bars 20, 30, and 59 from the mixture containing the melamine-based admixture stored at room temperature was 0.009 percent at 5 days, 0.027 percent at 26 days, 0.067 percent at 88 days, and 0.099 percent at 180 days when testing was stopped. These expansions are similar to those for the salt concrete mixture made with naphthalene-based HRWR shown in Table 14. Average expansions of 0.087 (restrained) at 153 days (Table 14) and 0.182 (unrestrained) at 365 days (Table 15); these are roughly twice as large as those for corresponding specimens and ages for the nonsalt concrete. Testing of unrestrained bars U1-2, U2-2, and U3-2 (Table 15) will continue at 6-month intervals.

31. Expansion data through 270-days testing of salt concrete and sanded salt grout, both cast 5 September 1984, are shown in Tables 16 and 17; these are the mixtures used in the pipe tests mentioned earlier. Present indications are that this batch of salt concrete is more expansive than that made in 1983 (Tables 14, 15). These measurements will continue. Table 17A from other work (Buck 1984) on the sanded salt grout (TT83) was included for comparison with Table 17 data.

32. Creep data for the two concretes are plotted in Figures 1 through 6. These tests were started when the two concretes were 28 days old and were continued through 1 yr. Figures 1, 2, 3 are for the nonsalt mixture, while Figures 4, 5, 6 are for the salt mixture. Figures 1 and 4 show individual curves for the pairs of creep and control cylinders. The fact that the pair of nonsalt control cylinders shrank during sealed autogenous storage at about 73^{o} F while the pair of salt control cylinders expanded was a matter of concern since it was known that bars made from the same two concrete mixtures were expansive (Tables 12, 13, 14, 15). Extensive investigation was made to verify that the shrinkage was real and not due to error or a failure to seal. It is believed that the data shown for the control specimens are valid. Figures 2 and 5 show single curves for each concrete that are the average for each set of four cylinders; these indicate similar strain response to loading since the differing behavior of control specimens tended to compensate for the creep differences shown in Figures 1 and 4. Finally, Figures 3 and 6 show specific creep and the derived creep formula for each concrete mixture. They show more creep for the weaker salt concrete mixture. The nonsalt concrete

mixture was loaded to about 23 percent of its 28-day compressive strength while the salt concrete mixture was loaded to about 37 percent of its 28-day compressive strength; these values can be calculated from data in Table 6 and the appropriate figures. Since aggregate was the same for both concretes, the creep would probably have been similar for both concretes if strengths and moduli of elasticity (E) had been similar. However, since E was 6.4 for the nonsalt mixture and only 4.1 for the salt mixture, creep should be different (McDonald 1975). Figure 44 from that work indicates the salt concrete should have about twice as much specific creep. This is in general agreement with Figures 3 and 6 in this report.

33. As indicated earlier, the results of the 1983 pipe stress tests will be incorporated with data now being obtained for some repeat testing started in September 1984. Present indications are that the basic reason for the problem with the 1983 test was that zero points need to be established prior to each test reading to compensate for shift that may have occurred. This was not feasible and was not done for the 1983 work. Use of a new automatic data acquisition system with the tests started in September 1984 meant that this could be done and it is.

34. Phase composition data for the two concretes through a little over 1 yr are shown in Table 18; these determinations will be continued at 6-month intervals. Table 18 shows that plaster was still detectable in the salt concrete mixture after 7 days but not thereafter; gypsum was detectable in the salt concrete at all ages but only at 7 days for the nonsalt concrete. Unhydrated cement is present in both concretes at all ages shown. Salt is detectable in the salt concrete through 97 days but not thereafter. Ettringite and calcium hydroxide are present in both concretes at all ages shown while tetracalcium aluminate dichloride-10-hydrate (chloroaluminate) is also present in the salt concrete. These compositions appear normal for these mixtures.

35. Approximately 60 SEM micrographs were made of the two concretes at 7- and 97-day ages and at their 13-month age to characterize their microstructure. Fourteen of these were selected to show typical features; they are shown in Figures 7 through 13. The captions generally indicate what is being shown. The much different strengths of the two mixtures were always evident as breaks tending to go around aggregate particles in the weaker salt concrete and through aggregate particles in the stronger nonsalt concrete (Figure 7). While the

microstructure of both concretes seems generally as expected, there are some possible differences or significant features as follows:

a. The size of discrete calcium silicate hydrate (C-S-H) particles seems smaller in the nonsalt concrete (Figures 8, 10).

b. No fibrous Type I C-S-H (Diamond 1976) was found in any of the samples examined. Normally, this type of C-S-H would be evident in hydrated pastes at 7 days. Apparently, the combination of materials used resulted in more of a Type III C-S-H structure (Diamond 1976).

c. The apparent shape of C-S-H seen in the salt concrete (Figures 8, 10) may be affected by possible secondary coating by salt on C-S-H surfaces. If so, this would be an artifact due to sample preparation.

d. The high air content of the salt concrete is seen in Figure 13a. The type of void linings commonly seen is shown in Figures 11b and 13b.

Discussion

Nonsalt concrete

36. A nonsalt concrete based on expansive BCT-1-FF grout was developed. Slight revision of the material that was tested is expected to provide a satisfactory concrete mixture; these revisions are described in this report.

37. The physical and thermal properties that were determined were considered to be generally satisfactory. Permeability was too low to be detected. Expansion was small, but it was positive. There is the possibility that expansion could be increased through additional experimentation, possibly by the use of gypsum for plaster or with a retarded plaster.

Salt concrete

38. A salt concrete based on expansive BCT-1-F salt grout was developed. There were significant problems because of excessive air contents due to the use of salt. It is believed that if a melamine type HRWR is used instead of a naphthalene HRWR, the air problems will be eliminated, and the concrete mixture will be satisfactory.

39. While the data for the hardened concrete were generally satisfactory, different air contents in the 15- and the 5-cu ft batches mean that one should correlate the data being studied with the air content of those specimens.

Nonsalt and salt concrete

40. There was little or no expansion of heated specimens. This is believed to be due to unintentional drying and not to a property of the concretes. If drying had not occurred, it is believed that expansion would have occurred.

Conclusions

41. Testing of two concrete mixtures through 2 yr indicates that both are viable candidate mixtures for repository sealing use against salt or nonsalt host rock. While the physical properties of the two mixtures are different, it is believed they would be generally similar if excess air in the salt mixture was eliminated. This can be achieved by use of a melamine-based HRWR in place of the naphthalene-based one that was used.

42. Comparison of the two concrete mixtures indicates:

a. Setting time was about twice as long for the salt concrete; this was approximately 1 day and may require 2 days.

b. There was much more formation of air with salt concrete when a naphthalene-based HRWR was used.

c. Salt concrete had lower but still adequate strength.

d. Salt concrete was a little more permeable, but this permeability is still very low; it was about 1 microdarcy or less in these tests.

e. Salt concrete gave about twice as much expansion. This maximum expansion was between 0.050 and 0.100 percent at 90 days. It was over 0.1 percent for unrestrained expansion at 1 yr.

f. Salt concrete had a lower modulus of elasticity and higher specific creep.

Recommendations

43. Tests for expansion and monitoring of phase composition and microstructure of both concrete mixtures should be continued at intervals of 6 or more months.

44. The pipe tests that were started in September 1984 should be continued as long as needed, perhaps a year, and a separate report of that work should be issued.

45. A full size batch of salt concrete (approximately 10 cu ft) should be made using a melamine-based HRWR and mixed intermittently for 2 hr to show

that air content would not be excessive. Specimens should be made and tested for a few selected properties to demonstrate the effect that excessive air in the 1983 mixture had on these properties.

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Roy, D. M., Grutzeck, M. W., Mather, K., and Buck, A. D., "PSU/WES Interlaboratory Comparative Methodology Study of An Experimental Cementitious Repository Seal Material," USAE Waterways Experiment Station, Miscellaneous Paper SL-81-2, Report 2, Final Results, Mar 1982, Vicksburg, Miss.

Table 1

TO Structures Laboratory Waterways Exp Station ATTN: Al Buck P. O. Box 631 Vicksburg, MS 39180	REPORT OF TESTS OF CEMENT RC 836 (2-4)	FROM: CORPS OF ENGINEERS U. S. ARMY Structures Laboratory Waterways Exp Station ATTN: Cem & Pozz Unit P. O. Box 631 Vicksburg, MS 39180

TEST REPORT NO. WES-93-83 | BIN NO. | CWT REPRESENTED: | DATE: 8 April 1983

SPECIFICATION: API, Class "H" | DATE SAMPLED: 15 March 1983

COMPANY: Dowell | LOCATION: Artesia, NM | BRAND:

THIS CEMENT DOES X MEET SPECIFICATION REQUIREMENTS

SAMPLE NO.	1				LOT	2	3	4
SiO_2, %	22.1					ORIGINAL ANALYSIS*		
Al_2O_3, %	3.6				Al_2O_3, %	3.9	3.4	4.2
Fe_2O_3, %	4.0				SO_3, %	2.1	2.2	2.7
MgO, %	2.7		Surface Area, m^2/kg			270	239	316
SO_3, %	2.6							
LOSS ON IGNITION, %	0.8				BARREL	1	2	3
ALKALIES-TOTAL AS Na_2O, %	0.51					BLENDED MATERIAL		*
Na_2O, %	0.14				Al_2O_3, %	3.88	3.89	3.92
K_2O, %	0.56				SO_3, %	2.62	2.59	2.59
INSOLUBLE RESIDUE, %	0.28		Surface Area, m^2/kg			297	296	297
CaO, %	63.7							
C_3S, %	54		Variation among barrels is well within					
C_3A, %	3		analytical error.					
C_2S, %	23							
$C_3A + C_3S$, %	57							
C_4AF, % $+ 2C_3A$	18							
HH Cure Temp	23° C	60° C			HEAT OF	23°C	60°C	
HEAT OF HYDRATION, 7D, CAL G	68**	74	W/C 0.40		HYDRATION			
HEAT OF HYDRATION, 28D, CAL G	78**	81**	W/C 0.40		3 DAY	62**	74	W/C 0.40
SURFACE AREA, m^2/kg (A.P.)	297							
AIR CONTENT, %	11							
COMP. STRENGTH, 3D, PSI	2420							
COMP. STRENGTH, 7D, PSI	3030							
COMP. STRENGTH, D, PSI								
FALSE SET-PEN. F I. %								
SAMPLE NO.								
AUTOCLAVE EXP., %	0.00							
INITIAL SET, Gillmore	2:30							
FINAL SET, Gillmore	4:45							
SAMPLE NO.								
AUTOCLAVE EXP., %								
INITIAL SET, HR/MIN								
FINAL SET, HR/MIN								

REMARKS: * Examination of test reports of RC836(2) - 836(4), suggested three analyses which varied sufficiently to be used as measures of homogeneity of the blended material. These analyses were: Al_2O_3, SO_3, and Blaine Fineness.

** Corrected 10/4/83.

THE INFORMATION GIVEN IN THIS REPORT SHALL NOT BE USED IN ADVERTISING OR SALES PROMOTION TO INDICATE EITHER EXPLICITLY OR IMPLICITLY ENDORSEMENT OF THIS PRODUCT BY THE U. S. GOVERNMENT

R. E. Reinhold

R. E. REINHOLD
Chief, Cement & Pozzolan Unit

ENG FORM 6000-R

Table 2

Physical Data for Natural Chert Gravel CL-43 G-2

Sieve Size		Individual % Retained
12.5 mm (1/2 in.)		4.9
9.5 mm (3/8 in.)		28.8
4.75 mm (No. 4)		60.6
Pan 2.36 mm (No. 8)		4.2
1.18 mm (No. 16)		1.0
<1.18 mm		0.5
	Total	100.0
Absorption, %*	1.4	
Specific Gravity*	2.6	

* CRD-C 107-82, Reference 2.

Table 3

Physical Data for Natural Sand CL-43 S-1

Sieve Size		Individual % Retained
4.75 mm (No. 4)		7.8
2.36 mm (No. 8)		11.0
1.18 mm (No. 16)		5.6
600 μm (No. 30)		10.5
300 μm (No. 50)		52.2
150 μm (No. 100)		11.0
Pan		1.9
	Total	100.0
Absorption, %*	0.54	
Specific Gravity*	2.62	

* CRD-C 108-81, Reference 2.

Table 4

Mixture Proportions and Other Data for a Nonsalt Concrete*

Material**	Amount to Make 1 cu yd, lb
Class H Cement	608.6
Fly Ash	204.8
Plaster	73.9
HRWR	17.3
Gravel (1/2-in. maximum size)	1400.6
Sand	1382.6
Water	285.2
Total	3973.0
Water-Cement Ratio	0.47
Water to Cementitious Solids Ratio (W/CSR)	0.32

Slump: Initial, 11 in.; 1/2 hr, 7-1/4 in.; 1 hr, 6-1/2 in.; 1-1/2 hr, 10 in.; 2 hr, 10 in.

Theoretical Unit Weight, 148.3 lb/cu ft
Sand to Gravel Ratio, 49 percent
Initial Set,† 14 hr 10 min
Final Set,† 16 hr

* Initial W/CSR should be decreased to 0.30 and ratio of HRWR to cement plus ash plus plaster adjusted to 1.5 percent. Adjust HRWR later if and as needed.

** Identified in report.

† CRD-C 86-81, Reference 2.

Table 5

Mixture Proportions and Other Data for a Salt Concrete Mixture

Material*	Amount to Make 1 cu yd, lb
Class H Cement	606.6
Fly Ash	204.0
Plaster	73.8
HRWR	9.8
Gravel (1/2-in. maximum size)	1396.0
Sand	1378.0
Salt (NaCl)**	98.5
De-Air Agent	4.4
Water	265.3
Total	4036.4
Water-Cement Ratio	0.44
Water to Cementitious Solids Ratio (W/CSR)	0.30

Slump: Initial, 9-1/4 in.

Air Content, Plastic: 11.8 percent for 14-cu ft batch, 6.8 percent for 6-cu ft batch

Theoretical Unit Weight: 149.3†

Sand to Gravel Ratio, 49 percent

Initial Set,†† 25 hr 15 min

Final Set,†† 32 hr 30 min

* Identified in report.

** *Amounts to 37.1 percent by weight of water.*

† Actual unit weights of 3- by 6-in. cylinders CL-43 CON-1(S) and 46(S) were 135.4 and 141.6 lb/cu ft, respectively.

†† CRD-C 86-81, Reference 2.

Table 6

Modulus of Elasticity and Compressive Strength of Nonsalt and Salt Concrete

Specimens at Two Ages and Two Temperatures

	Nonsalt Concrete/Salt Concrete*			
	7-days Age			
	23 ± 1.7° C**	61 ± 2° C†	23 ± 1.7° C**	61 ± 2° C†
	CL-43 CON-21	CL-43 CON-22	CL-43 CON-34(S)	CL-43 CON-35(S)
Modulus of Elasticity, E x 10^6 psi	5.4	6.8	3.8	4.6
Compressive Strength, psi	5460	11,250	2830	4670
	28-days Age			
	CL-43 CON-23	CL-43 CON-24	CL-43 CON-36(S)	CL-43 CON-37(S)
Modulus of Elasticity, E x 10^6 psi	6.4	6.9	4.1	4.8
Compressive Strength, psi	8810	14,270	3710	6600

* From 6-cu ft batch with 6.8 percent air.

** Moist cured.

† Sealed to prevent moisture after stripping; heated; cooled overnight before testing.

Table 7[a]

Strength of Nonsalt Bearing Concrete at Two Temperatures

Kind of Strength	Moist Cured at 23 ± 1.7° C — Test Ages, days[b]: 1	7	28	91	180	365[c]
Compressive, psi	(1) 2,810 (34) 2,100	(2) 5,350 (35) 5,420	(5) 8,260 (38) 8,250	(7) 10,280 (40) 10,040	(9) 11,840 (42) 12,150	(54-2) 13,130 (54-3) 13,820 (55-2) 13,310
Average	2,460	5,380	8,260	10,160	12,000	13,090
Tensile, psi	Not Determined	(3) 730 (36) 700	(6) 1,020 (29) 1,000	(8) 1,350 (41) 1,260	(10) 1,280 (43) 1,280	(54-1) 1,390 (55-1) 1,280 (55-3) 1,390
Average		720	1,010	1,300	1,280	1,350
	Stored at 61 ± 2° C[d]					
Compressive, psi	Not Determined	(11) 9,770 (44) 10,650	(13) 12,010 (46) 10,520	(15) 11,000 (48) 12,280	(17) 14,030 (50) 14,290	(19) 11,530 (52) 14,440
Average		10,210	11,260	11,640	14,160	12,990
Tensile, psi	Not Determined	(12) 1,230 (45) 1,200	(14) 1,370 (47) 1,270	(16) 1,510 (49) 1,480	(18) 1,480 (51) 1,400	(20) 1,560 (53) 1,580
Average		1,220	1,320	1,490	1,440	1,570

(a) Revised to add 180- and 365-day data.

(b) Numbers in parentheses are the specimen numbers that follow CL-43 CON-__. No. 1 through 20 were from 14-cu ft batch and 34 through 55 were from 6-cu ft batch.

(c) Since all moist-cured 3- by 6-in. cylinders had been used, two 3- by 20-in. cylinders (54, 55) were cut and tested.

(d) Cooled overnight before tested.

Table 7A

Compressive Strength of Nonsalt Concrete Cylinders

Cast 24 May 1984

Specimen Identification	Compressive Strength, psi, at Ages Indicated Below, days		
	7	28	90
CL-43 CON-			
1[a]-2	4160		
	4570		
Average	4360 (5380)[b]		
2[a]-2		6850	
		7090	
Average		6970 (8260)[b]	
3[a]-2			9,590
			9,720
Average			9,660 (10,160)[b]

(a) Specimens were cast in 3- by 20-in.-long cardboard cylinder molds. Two 3- by 6-in. cylinders were cut from a 3- by 20-in. cylinder for a test age.
(b) Comparative values from Table 7.

Table 8[a]

Strength of Salt Concrete at Two Temperatures[b]

Kind of Strength	4	7	28	90	180	365
	Moist Cured at 23 ± 1.7° C					
	Test Ages, days[c]					
Compressive, psi	(1S) 1,840	(2S) 2,190	(4S) 2,660	(6S) 2,920	(8S) 2,340	(10S) 3,470
	(46S) 2,380	(47S) 2,700	(49S) 3,470	(51S) 3,290	(53S) 3,180	(55S) 3,370
Tensile, psi	Not	(3S) 300	(5S) 360	(7S) 400	(9S) 430	(11S) 510
	Determined	(48S) 420	(50S) 460	(52S) 460	(54S) 500	(56S) 580
	Stored at 61 ± 2° C[d]					
Compressive, psi	Not	(14S) 3,690	(16S) 4,700	(18S) 5,370	(20S) 5,390	(22S, 23S) 5,280[f]
	Determined	(59S) 4,550	(61S) 6,110	(63S) 7,070	(65S) 6,810	(67S, 68S) 8,140[f]
Tensile, psi	Not	(15S) 460	(17S) 580	(19S) 660	(21S) 650[e]	(24S, 25S) 6,250[f]
	Determined	(60S) 620	(62S) 760	(64S) 700	(66S) 800	(69S, 70S) 850[f]

(a) Revised to add 180- and 365-day data.

(b) Numbers in parentheses are the specimen numbers that follow CL-43 CON-__. No. 1 through 25 were from 15-cu ft batch and 46 through 70 were from 5-cu ft batch.

(c) Specimens between 1 and 25 came from batch with 11.8 percent air; others are from batch with 6.5 percent air. Those with the higher air content should be and were usually about 25 percent weaker.

(d) Cooled overnight before tested.

(e) May be slightly in error because total load was erased before it was recorded.

(f) Average of two specimens.

Table 8A

Compressive Strength of Salt Concrete Cylinders Cast 24 May 1984

Specimen Identification	Compressive Strength, psi, at Ages Indicated Below, days		
	7	28	90
CL-43 CON-			
1[a]-2(S)	1740		
	1700		
Average	1720 (2190, 2700)[b]		
2[a]-2(S)		2380	
		2320	
Average		2350 (2660, 3470)[b]	
3[a]-2(S)			3030
			3470
Average			3250 (2920, 3290)[b]

(a) Specimens were cut in 3- by 20-in.-long cardboard cylinder molds. Two 3- by 6-in. cylinders were cut from a 3- by 20-in. cylinder for a test age.
(b) Comparative values from Table 8.

Table 9

Liquid Permeability Data on Nonsalt and Salt Concrete

Permeability in Microdarcies	
Nonsalt Concrete	**Salt Concrete**
Cylinder CL-43 CON-25*	Cylinder CL-43 CON-75(S)*
One 6- by 6-in. cylinder leaked and was discarded One 6- by 6-in. cylinder did not pass any water in 18 days so there was no detectable permeability.	6- by 6-in. top half of 6- by 12-in. cylinder permeability was 1.1 microdarcy. The bottom half leaked so there were no data.
3- by 6-in. cylinders CL-43 CON-4, 37** no detectable permeability after 17 days of testing.	3- by 6-in. cylinder CL-43 CON-58(S)** gave 0.01 microdarcies

* Tested in accordance with CRD-C 48-73.

** Tested in Hassler cell with same end pressure (200 psi) as for CRD-C 48-73.

Table 10

Coefficient of Linear Thermal Expansion Data*

	Coefficient of Linear Thermal Expansion, $10^{-6}/^{o}$ F**			
	Nonsalt Concrete†		Salt Concrete†	
	CL-43 CON		CL-43 CON	
	-32	-33	-44(S)	-45(S)
Cycle 1	7.39	6.99	7.19	7.12
Cycle 2	7.39	7.38	7.08	6.88
Cycle 3	7.09	7.22	6.86	6.86
Average	7.29	7.20	7.04	6.95
Average of Two Specimens	7.24		7.00	

* Done in accordance with CRD-C 39-81 over temperature range of 4.4° C to 60° C.

** To express in SI units of 10^{-6} per ° C, multiply by 9/5.

† Each specimen was a 6- by 16-in. cylinder with an embedded Carlson strain meter.

Table 11

Thermal Conductivity Data at 28-Days Age*

Properties Determined	Nonsalt Concrete** CL-43 CON -26	-27	Salt Concrete** CL-43 CON -38(S)	-39(S)
Thermal Diffusivity (α),† ft^2/hr	0.0424	0.0428	0.0360	0.0360
Average	0.0426		0.0360	
Specific Heat (S),†† Btu/lb-F	0.219	0.226	0.235	0.234
Average	0.222		0.234	
Apparent Density (ρ), lb/ft^3	149.8	150.3	142.4	142.2
Average	150.1		142.3	
Thermal Conductivity (K),*** Btu/ft^2-hr-deg F/ft	1.391	1.454	1.204	1.198
Average K***	1.422		1.201	

* Done in accordance with CRD-C 44-63.

** Each specimen was a 6- by 12-in. cylinder with an embedded thermocouple in it.

*** To express in SI units of watts per metre per deg Kelvin, multiply by 0.01201899.

† To express in SI units of m^2/sec, multiply by 0.0000258064.

†† To express in SI units of joules per kilogram per deg Kelvin, multiply by 4186.8.

Table 12[a]

Restrained Expansion of 3- by 3- by 10-in. Nonsalt Concrete

Bars at Two Temperatures

Age, days(c)	Stored at 23 ± 1.7° C				Sealed and Stored at 61 ± 2° C(b)			
	Length Changes, %							
	R1	R2	R3	Average	R4	R5	R6	Average
1	0.003	0.003	0.003	0.003	-0.006	-0.005	-0.004	-0.005
4	0.006	0.009	0.008	0.008	-0.010	-0.009	-0.006	-0.008
7	0.009	0.013	0.013	0.012	-0.014	-0.012	-0.009	-0.012
9	0.010	0.015	0.015	0.013	-0.017	-0.013	-0.011	-0.014
11	0.013	0.018	0.018	0.016	-0.017	-0.014	-0.012	-0.014
14	0.014	0.018	0.019	0.017	-0.018	-0.013	-0.012	-0.014
21	0.019	0.023	0.025	0.022	-0.023	-0.019	-0.018	-0.020
28	0.021	0.025	0.028	0.025	-0.025	-0.022	-0.021	-0.023
56	0.030	0.032	0.038	0.033	-0.026	-0.024	-0.022	-0.024
92	0.037	0.039	0.045	0.040	-0.026	-0.026	-0.024	-0.025
						(d)		
365	0.039	0.044	0.051	0.045				
31					0.009	0.009	0.009	0.009
211					0.028	0.030	0.014	0.024
Age, years								
1-1/2	0.044	0.048	0.056	0.049				
2	0.049	0.053	0.061	0.054				

(a) Revised to add data after the initial 92 days of testing.

(b) Cooled overnight to room temperature. All bars measured at same room temperature (20 to 27-1/2° C).

(c) Made 18 April 1983; initial length read when stripped on 19 April after overnight in moist cabinet. Thus, bars are actually 1 day older than indicated.

(d) Seal removed from bars R4, R5, R6 at about 140-days age; new reference length measured at room temperature. Bars then put into moist storage. Testing stopped after the 1-year reading.

Table 13[a]

Unrestrained Expansion of 3- by 3- by 10-in. Nonsalt Concrete Bars at Two Temperatures

Age, days[c]	Stored at 23 ± 1.7° C				Sealed and Stored at 61 ± 2° C[b]		
	Length Changes, %[d]						
	U1	U2	U3	Average	U4	U5	Average
1	0.007	0.006	0.006	0.006	-0.010	-0.010[e]	-0.010
4	0.015	0.018	0.013	0.015	-0.018	-0.017[e]	-0.018
7	0.021	0.020	0.017	0.019	-0.023	-0.015[e]	-0.019
9	0.026	0.026	0.023	0.025	-0.026	-0.012[e]	-0.019
11	0.030	0.030	0.027	0.029	-0.027	-0.012	-0.020
14	0.035	0.034	0.031	0.033	-0.029	-0.027	-0.028
21	0.044	0.041	0.029	0.038	-0.036	-0.035	-0.036
28	0.048	0.045	0.033	0.042	-0.038	-0.039	-0.038
56	0.064	0.060	0.047	0.057	-0.040	-0.040	-0.040
92	0.070	0.067	0.053	0.063	-0.040	Not read	--
						(f)	
365	0.080	0.075	0.060	0.072			
31					0.013	0.004	0.008
211					0.034	0.002	0.018
Age, years							
1-1/2	0.083	0.082	0.072	0.079			
2	0.091	0.090	0.080	0.087			

(a) Revised to add data after the initial 92 days of testing.

(b) Cooled overnight to room temperature. All bars measured at same room temperature (20 to 27-1/2° C).

(c) Made 18 April 1983; initial length read when stripped on 19 April after overnight in moist cabinet. Thus, bars are actually 1 day older than indicated.

(d) Bar 6 was defective and was discarded.

(e) Calculated by comparison with U4.

(f) Seal removed from bars U4 and U5 at about 140-day age; new reference length measured at room temperature. Bars then put into moist storage. Testing stopped after the 1-year reading.

Table 14[a]

Restrained Expansion of 3- by 3- by 10-in. Salt Concrete Bars at Two Temperatures

Age, days[c]	Stored at 23 ± 1.7° C				Sealed and Stored at 61 ± 2° C[b]			
	Length Changes, %							
	R1-2	R2-2	R3-2	Average	R4-2	R5-2	R6-2	Average
1	0.010	0.008	0.010	0.009	n. d.[d]	n. d.	n. d.	--
3	0.014	0.011	0.012	0.012	0.005	0.004	0.001	0.003
5	0.017	0.014	0.015	0.015	-0.001	0.003	0.001	0.001
7	0.017	0.015	0.015	0.016	n. d.	n. d.	n. d.	--
9	0.019	0.016	0.018	0.018	n. d.	n. d.	n. d.	--
11	0.024	0.021	0.025	0.023	0.003	0.001	0.004	0.003
13	0.027	0.022	0.024	0.024	n. d.	n. d.	n. d.	--
15	0.027	0.024	0.026	0.026	0.004	0.005	0.002	0.004
17	0.030	0.031	0.027	0.029	n. d.	n. d.	n. d.	--
26	0.042	0.042	0.038	0.041	0.002	-0.003	-0.003	-0.001
54	0.053	0.063	0.056	0.057	0.008	-0.012	-0.008	-0.004
88	0.063	0.077	0.072	0.071	0.009	-0.013	-0.006	-0.003
153[e]	0.079	0.093	0.088	0.087	Discontinued			

(a) Revised to add data beyond 88 days.
(b) Cooled overnight to room temperature. All bars measured at same room temperature (20 to 27-1/2° C).
(c) Made 19 May 1983; initial length read when stripped on 21 May after 48 hr in moist cabinet. Thus, bars are actually 2 days older than indicated.
(d) Not determined.
(e) Final readings.

Table 15[a]

Unrestrained Expansion of 3- by 3- by 10-in. Salt Concrete Bars at Two Temperatures

Age, days[c]	Stored at 23 ± 1.7° C				Sealed and Stored at 61 ± 2° C[b]			
	Length Changes, %							
	U1-2	U2-2	U3-2	Average	U4-2	U5-2	U6-2	Average
3	0.026	0.026	0.018	0.023	0.003	0.008	0.002	0.004
5	0.030	0.031	0.023	0.028	n. d.[d]	n. d.	n. d.	--
7	0.034	0.030	0.024	0.029	0.003	0.009	0.003	0.005
9	0.037	0.034	0.027	0.033	n. d.	n. d.	n. d.	--
11	0.049	0.041	0.035	0.042	0.005	0.012	0.003	0.007
13	0.051	0.041	0.036	0.043	n. d.	n. d.	n. d.	--
15	0.056	0.043	0.037	0.045	0.004	0.012	0.003	0.006
17	0.057	0.043	0.037	0.046	n. d.	n. d.	n. d.	--
19	0.068	0.056	0.044	0.056	-0.009	0.009	0.000	0.000
26	0.082	0.059	0.053	0.065	-0.010	0.006	-0.004	-0.003
54	0.107	0.079	0.074	0.087	-0.020	-0.011	-0.012	-0.014
88	0.125	0.098	0.093	0.105	-0.027	-0.020	-0.018	-0.022
						Discontinued		
365	0.179	0.190	0.177	0.182				
Age, years								
1-1/2	0.200	0.224	0.209	0.211				
2	0.225	0.250	Lost	0.238				

(a) Revised to add data beyond 88 days.
(b) Cooled overnight to room temperature. All bars measured at same room temperature (20 to 27-1/2° C).
(c) Made 19 May 1983; initial length read when stripped on 21 May after 48 hr in moist cabinet. Thus, bars are actually 2 days older than indicated.
(d) Not determined.

Table 16

Length-Change Data for Nine Salt Concrete Bars Cast 5 September 1984[a]

	Length Changes, %, of Bars Shown Below[b]											
	Unrestrained 3-in. Bars				Restrained 3-in. Bars				Restrained 2-in. Bars			
Age, days	12	13	14	Average	15	16	17	Average	18	19	20	Average
7	0.043	0.040	0.047	0.043	0.026	0.023	0.025	0.025	0.029	(c)	(c)	0.029
14	0.061	0.060	0.068	0.063	0.040	0.034	0.036	0.037	0.046	0.046	0.039	0.044
21	0.077	0.075	0.086	0.079	0.051	0.045	0.047	0.048	0.056	0.062	0.052	0.057
28	0.095	0.095	0.106	0.099	0.062	0.055	0.056	0.058	0.068	0.072	0.062	0.067
56	0.146	0.155	0.155	0.152	0.085	0.076	0.077	0.079	0.095	0.100	0.090	0.095
90	0.193	0.226	0.204	0.208	0.112	0.103	0.100	0.105	0.114	0.126	0.109	0.116
180	0.286	0.327	0.293	0.302	0.164	0.149	0.148	0.154	0.161	0.169	0.163	0.164
270	0.362	0.413	0.373	0.383	0.202	0.188	0.194	0.195	0.197	0.202	0.185	0.195

(a) All bars in moist storage at approximately 73° F. Reference length was length when demolded.
(b) Initial length read when bars stripped at 48-hr age. Age is from date of fabrication.
(c) Failed to read.

Table 17

Length-Change Data for Nine Sanded Salt Grout (TT83) Bars Cast 5 September 1984[a]

Age, days	Length Changes, %, of Bars Shown Below											
	Unrestrained 3-in. Bars[b]				Restrained 3-in. Bars[c]				Restrained 2-in. Bars[c]			
	1	2	3	Average	4	5	6	Average	7	8	9	Average
7	0.060	0.045	0.026	0.044	0.037	0.022	0.039	0.033	0.023	0.016	0.023	0.021
14	0.068	0.071	0.049	0.063	0.046	0.032	0.048	0.042	0.037	0.028	0.035	0.033
21	0.067	0.083	0.066	0.072	0.057	0.040	0.061	0.053	0.048	0.040	0.046	0.045
28	0.096	0.101	0.093	0.097	0.066	0.053	0.070	0.063	0.062	0.053	0.059	0.060
56	0.201	0.187	0.157	0.182	0.109	0.097	0.115	0.107	0.124	0.121	0.120	0.122
90	0.326	0.298	0.294	0.306	0.150	0.145	0.159	0.151	0.184	0.186	0.186	0.185
180	0.552	0.531	0.520	0.534	0.295	0.304	0.317	0.305	0.311	0.301	0.300	0.304
270	0.762	0.739	0.736	0.746	0.379	0.393	0.403	0.392	0.368	0.357	0.361	0.362

(a) All bars in moist storage at about 73° F.
(b) Reference length was length when bars were demolded.
(c) Reference length was cage length read before bars were made.

Table 17A[a]

Restrained Expansion of BCT 1-F Salt Grout Containing Sand[b]

Age, days	Length Changes, %					
	3- by 3- by 10-in. Bars			2- by 2- by 10-in. Bars		
	No. 12	No. 25	Average	No. 43	No. 47	Average
5	0.013	-0.010	0.002	0.001	0.006	0.004
7	0.030	0.031	0.030	0.011	0.015	0.013
28	0.056	0.061	0.058	0.044	0.031	0.038
47	0.073	0.082	0.078	0.059	0.051	0.055
90[c]				0.129	0.093	0.111
180	0.184	0.210	0.197	0.218	0.191	0.204
365	0.353	0.384	0.368	0.387	0.368	0.378

(a) This is Table 2 in WES-SL Grout Report, dated 10 September 1984, subject, "Additional Data on TT83 Grout Through August 1984," (Buck 1984).

(b) Cast 13 July 1983; stored and measured at 23 $\pm$ 1.7° C. Since bars were not stripped until they were 5 days old, the reference length is the cage length before casting.

(c) Data for bars 12 and 25 were in error and were deleted.

Table 18

Phase Composition by X-Ray Diffraction (XRD) of the Cement Paste Portions of Two Concrete Mixtures at Different Ages[(a)]

	Phases Identified in Each Mixture											
	Original Phases						Hydration Phases[(b)]					
	Unhydrated Cement[(c)]		Calcium Sulfate		Salt		Ettringite[(d)]		Chloroaluminate		Calcium Hydroxide	
Test Age	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S
7 days	X	X	n. d.,[(e)] Gypsum	Plaster, Gypsum	n. d.	X	X	X	n. d.	X	X	X
28 days	X	X	n. d.	Plaster, Gypsum	n. d.	X	X	X	n. d.	X	X	X
97 days	X	X	n. d.	Plaster, Gypsum	n. d.	X	X	X	n. d.	X	X	X
13 months	X	X	n. d.	Plaster, Gypsum	n. d.	n. d.	X	X	n. d.	X	X	X

(a) A nonsalt-bearing concrete mixture (NS) was cast 18 April 1983. A salt-bearing concrete mixture (S) was cast 19 May 1983. Additional small batches of each mixture were made 24 May 1984. The 1984 concretes were examined at 7-, 28-, and 97-day ages. The 1983 concretes were examined after that time.
(b) Calcium silicate hydrate was present but not readily recognized by XRD.
(c) Alite, belite, and aluminoferrite.
(d) There was usually the possibility that a little monosulfoaluminate was also present.
(e) Not detected.

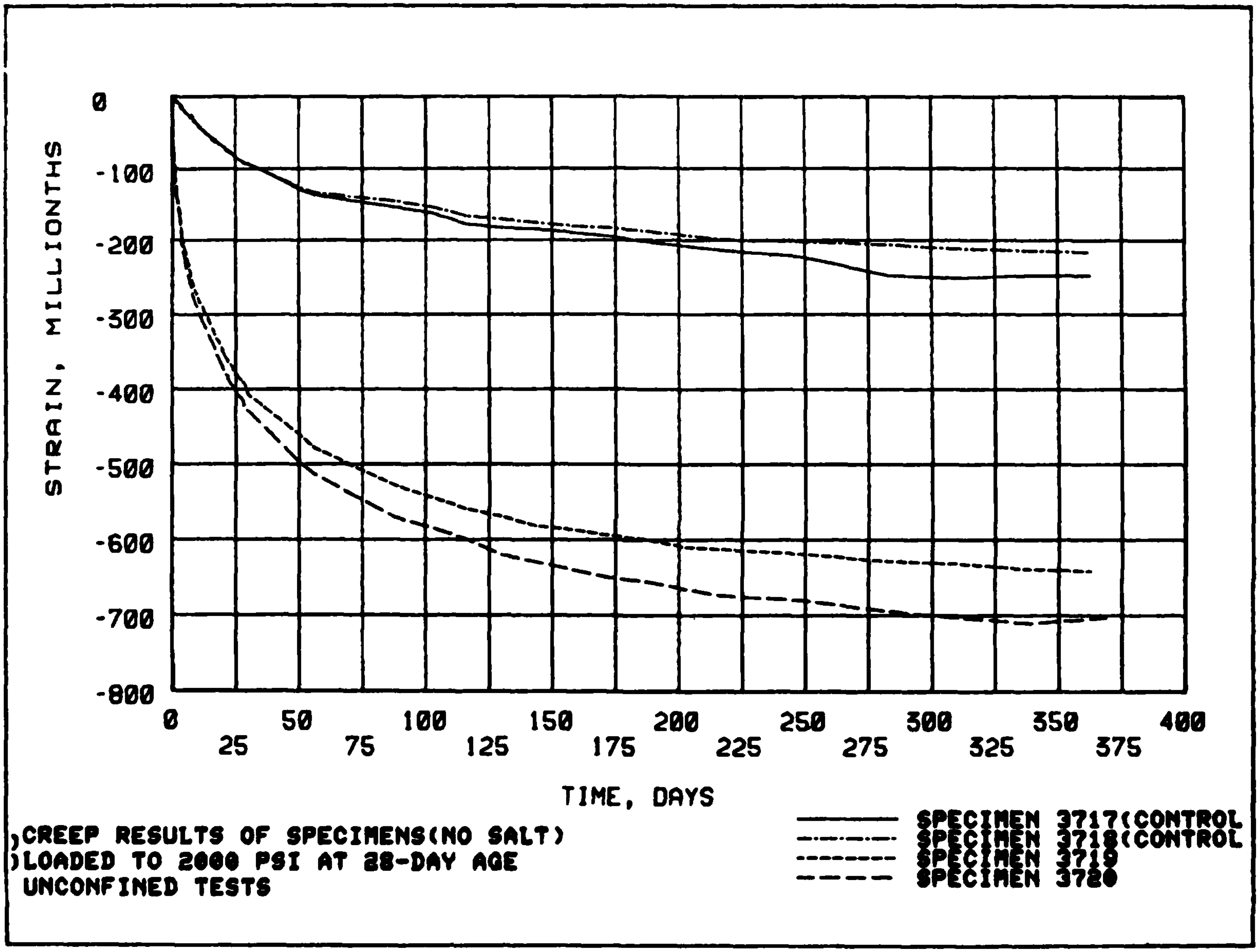


Figure 1. Creep data for nonsalt concrete cylinders CL-43 CON-28, 29, 30, 31

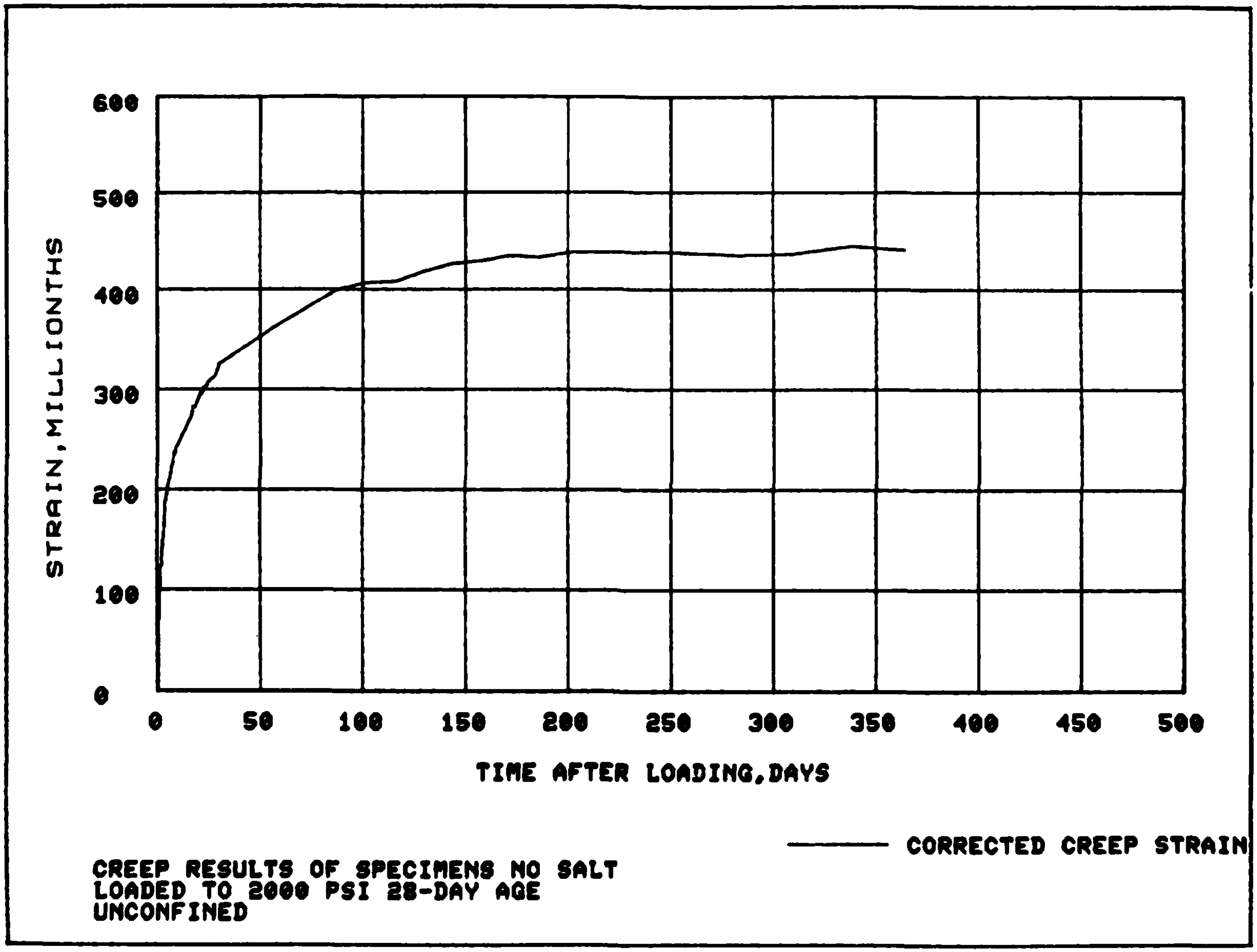


Figure 2. Average creep data for nonsalt concrete cylinders CL-43 CON-28, 29, 30, 31. This shows algebraic addition of the previous four curves

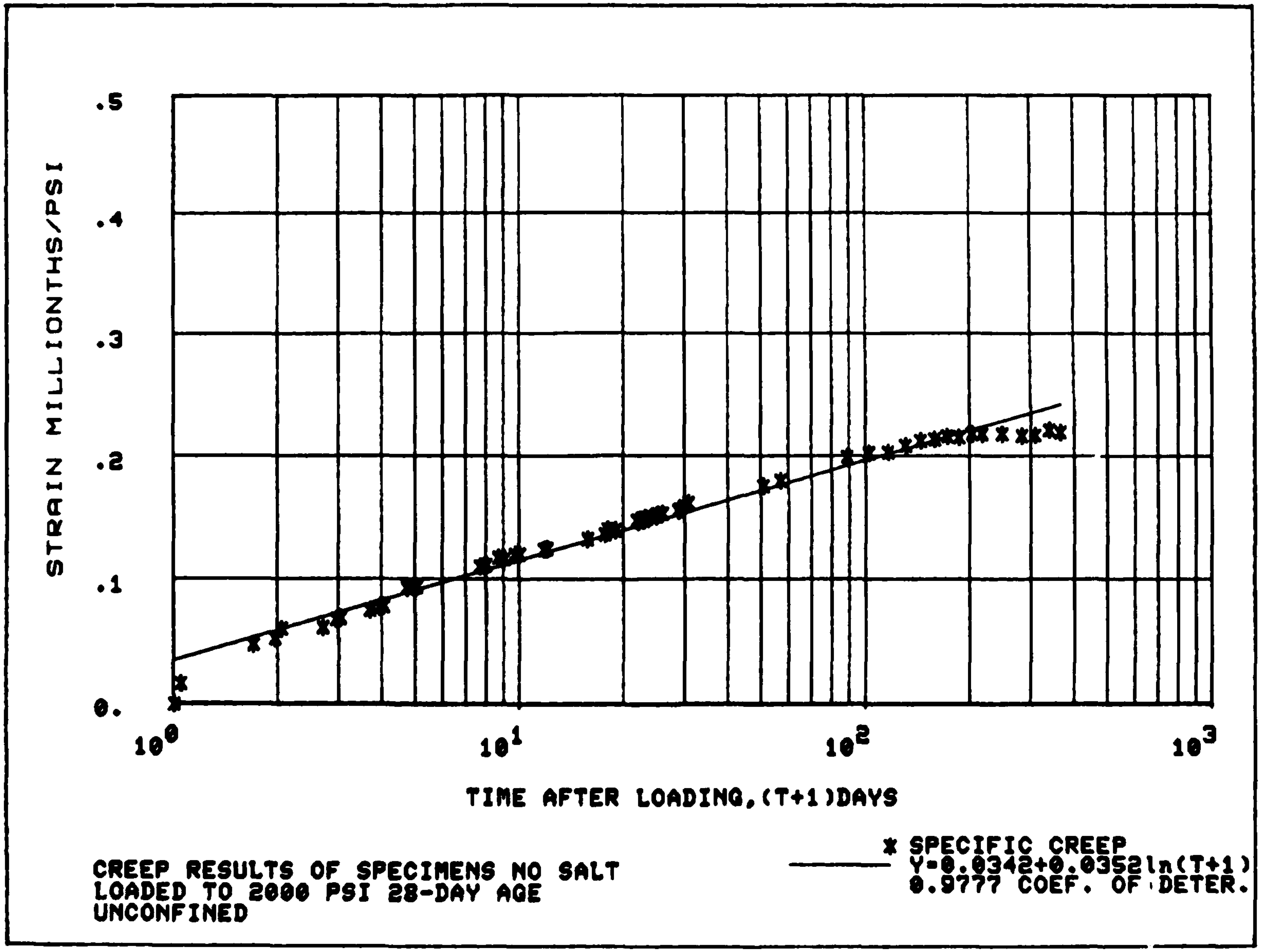


Figure 3. Average specific creep of nonsalt concrete cylinders CL-43 CON-28, 29, 30, 31. Specific creep is strain in millionths divided by load

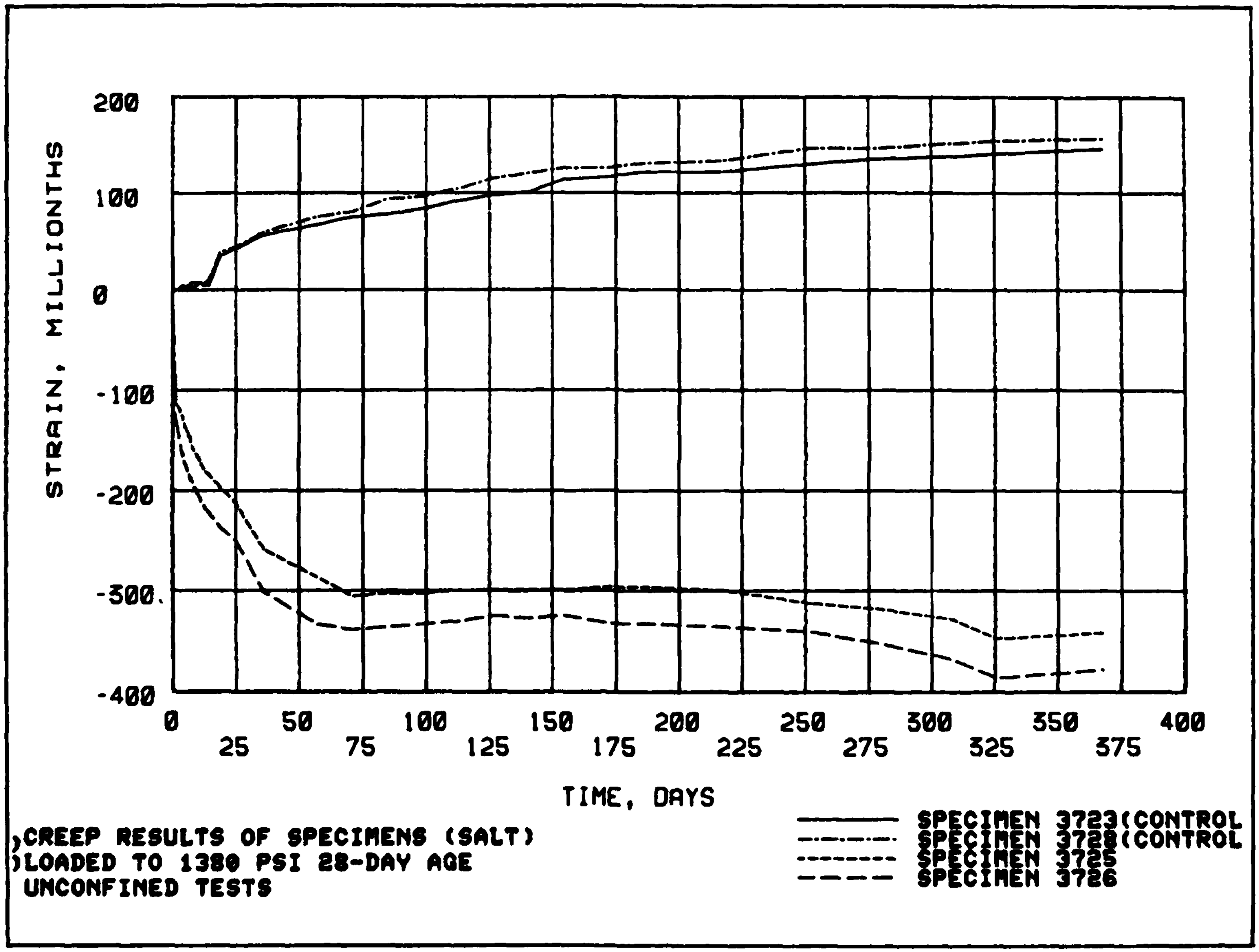


Figure 4. Creep data for salt concrete cylinders CL-43 CON-40(S) through 43(S)

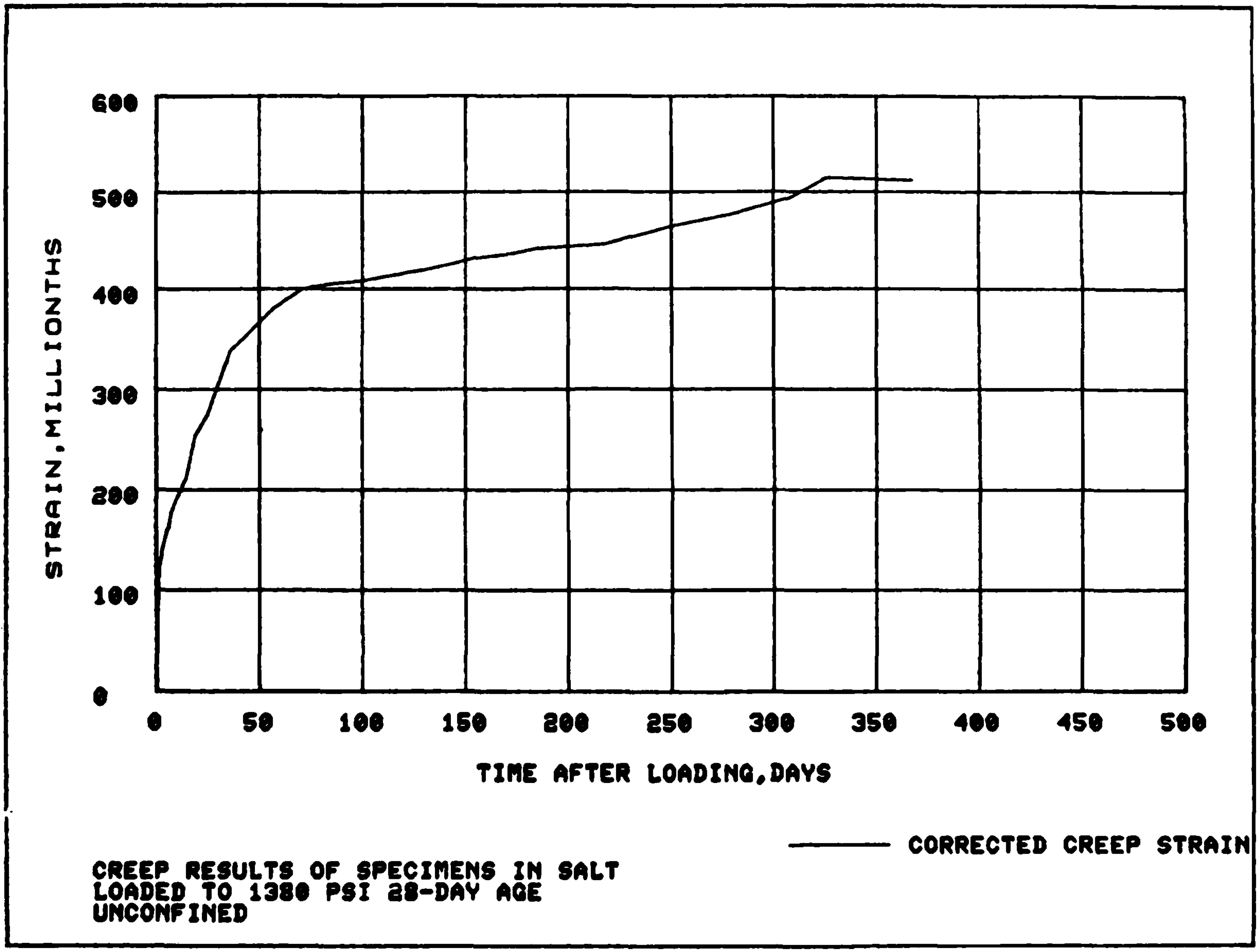


Figure 5. Average creep data for salt concrete cylinders CL-43 CON-40(S) through 43(S). This shows algebraic addition of the four curves in Figure 4

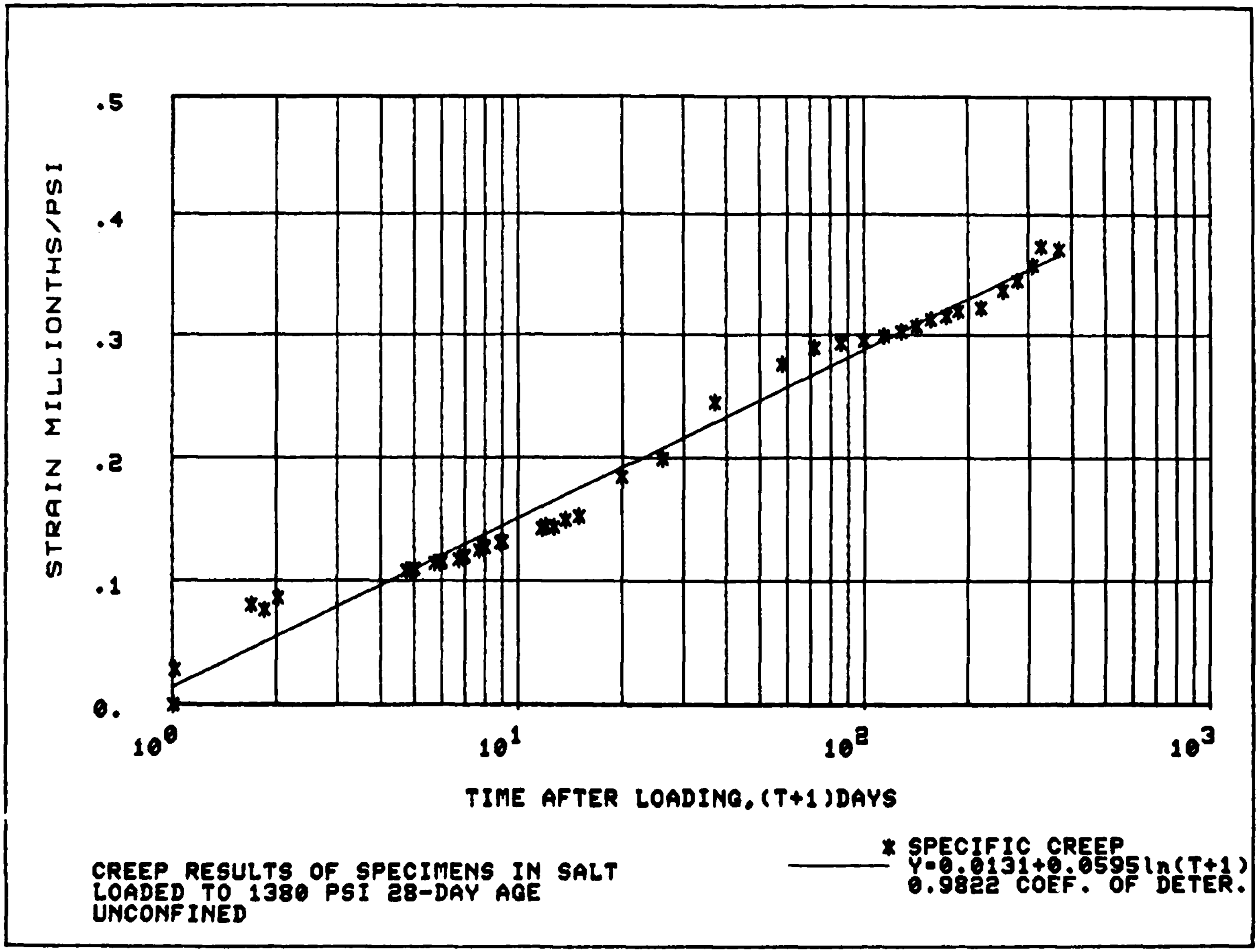
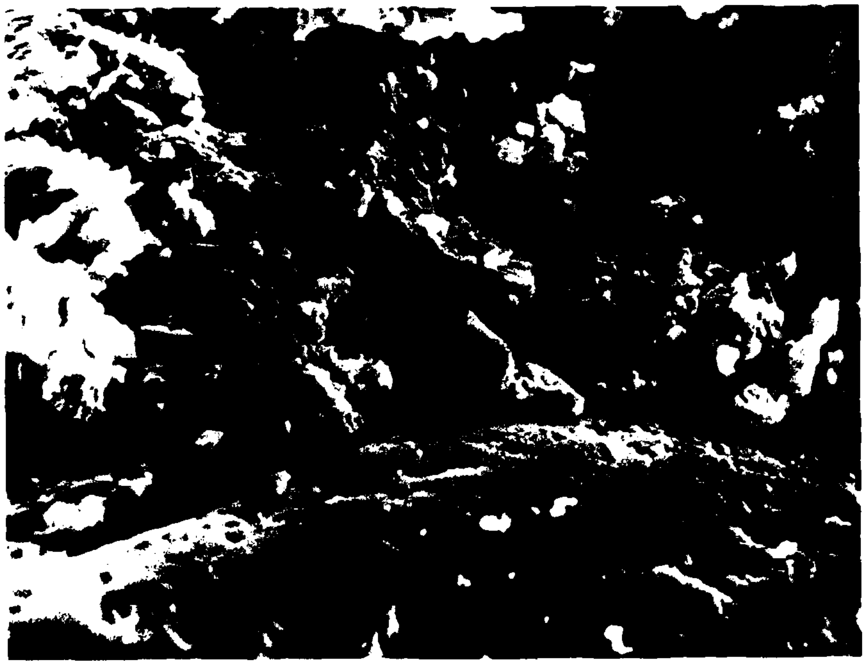


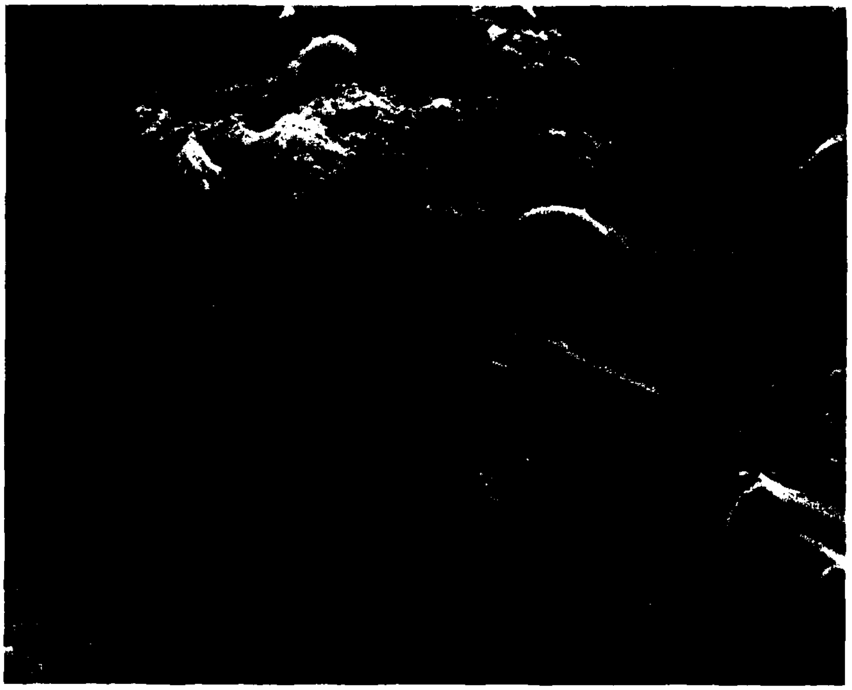
Figure 6. Average specific creep of salt concrete cylinders CL-43 CON-40(S) through 43(S). Specific creep is strain in millionths divided by load

a. Micrograph 062784-3 of nonsalt concrete at 7-days age, X980. Shows contact between mortar (top) and fractured rock (below)



b. Micrograph 070584-5 of salt concrete at 7-days age, X1030. Shows contact between mortar (top) and intact rock (below)

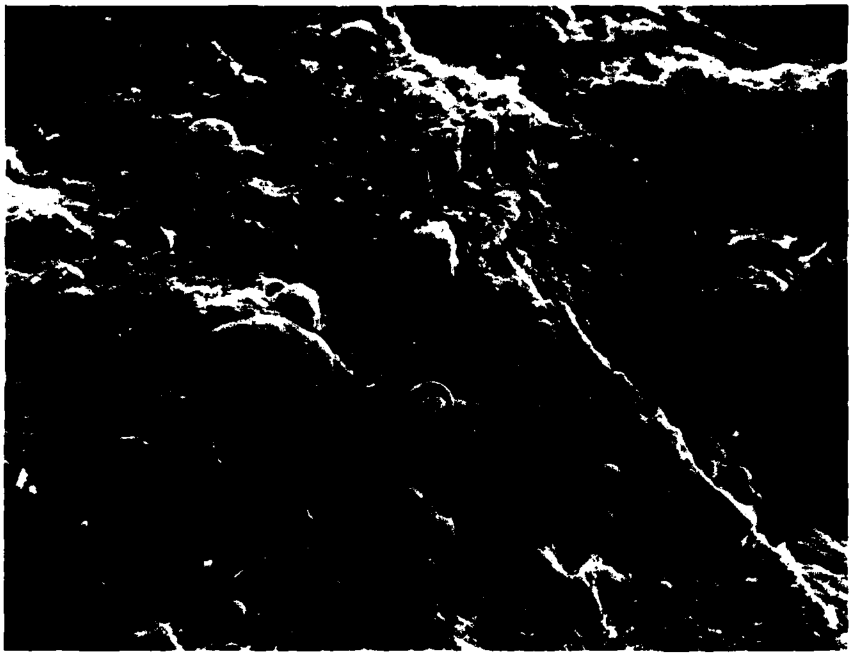
Figure 7



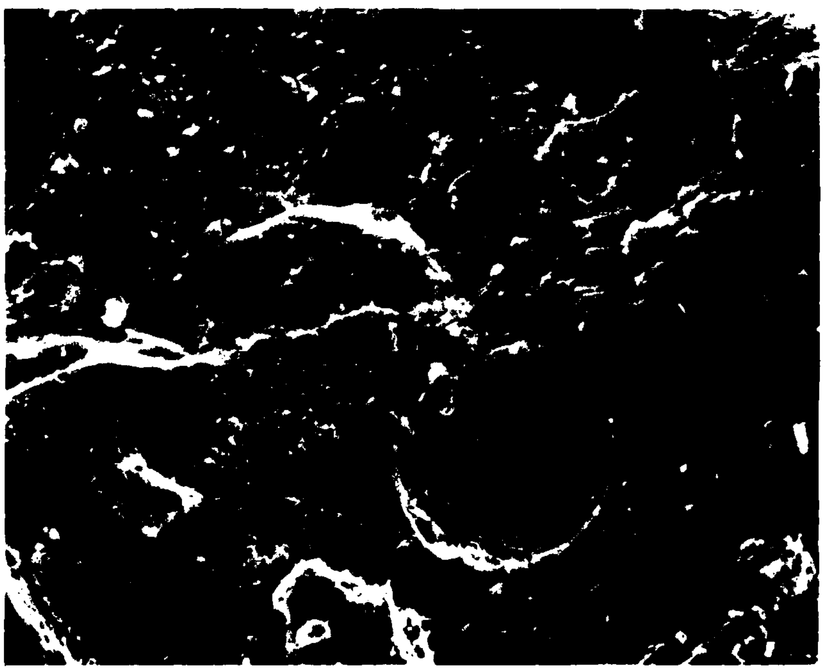
a. Micrograph 062784-6 of nonsalt concrete at 7-days age, X4900. Shows C-S-H (matrix), CH (lower right), fly ash spheres, and ettringite laths (left)

b. Micrograph 070484-7 of salt concrete at 7-days age, X5150. Shows stubby C-S-H (matrix) and tabular gypsum (?) crystal at left

Figure 8

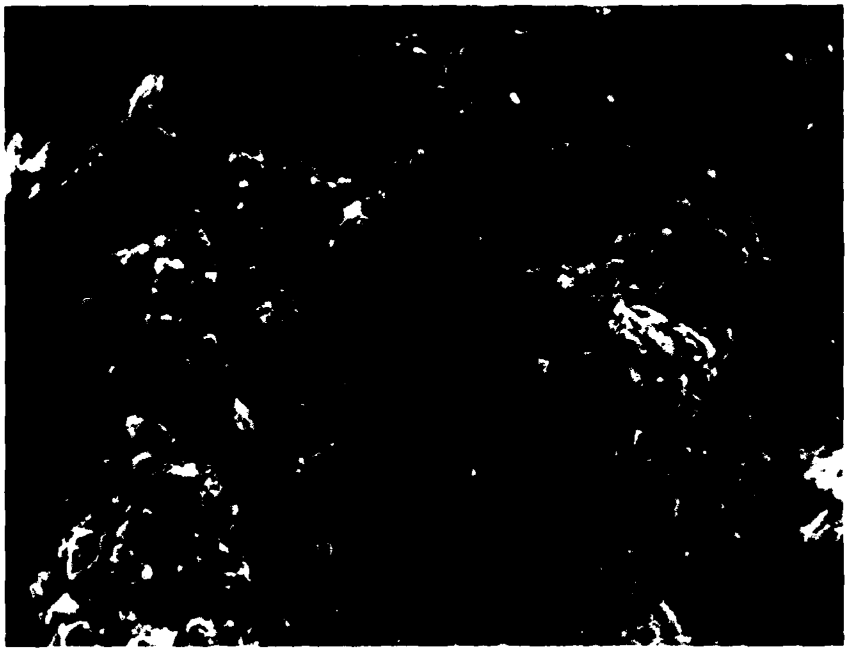


a. Micrograph 090784-3 of nonsalt concrete at 97-days age, X485. Matrix of dense C-S-H with scattered embedded fly ash spheres and residual cement grain (left center)



b. Micrograph 090784-24 of salt concrete at 97-days age, X465. C-S-H matrix, air void, fly ash spheres, and residual cement grain (upper center)

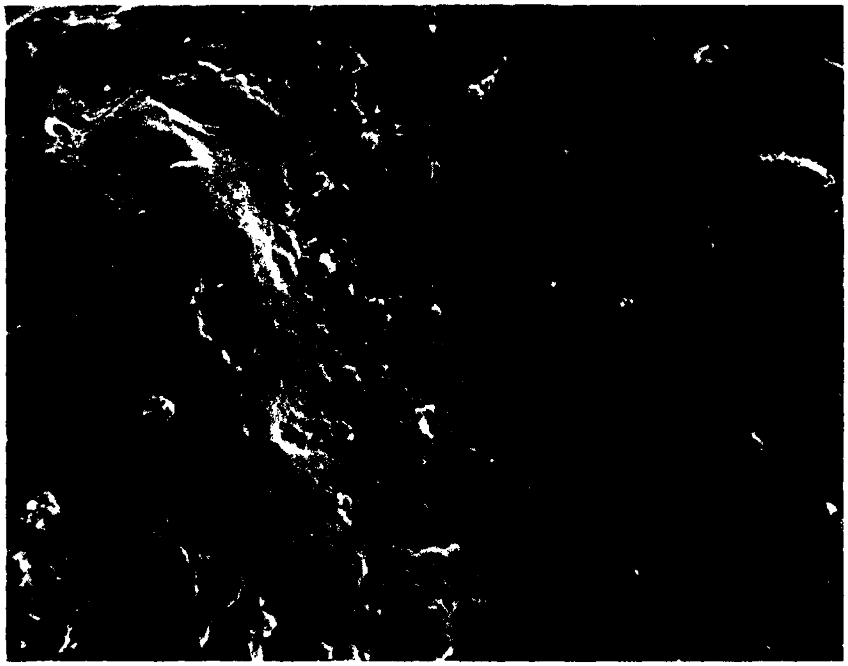
Figure 9



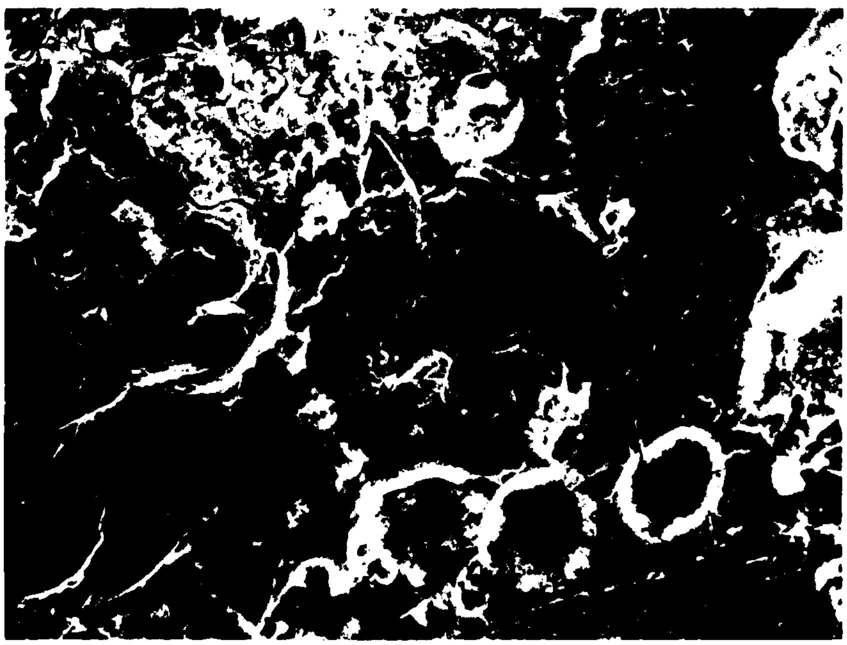
a. Micrograph 090784-8 of nonsalt concrete at 97-days age, X10,000. Shows mainly a dense C-S-H matrix

b. Micrograph 090784-22 of salt concrete at 97-days age, X4650. Open matrix of wormy C-S-H around residual cement grain. Light colored fibers near center and to right side are probably salt. Ettringite laths in upper left

Figure 10



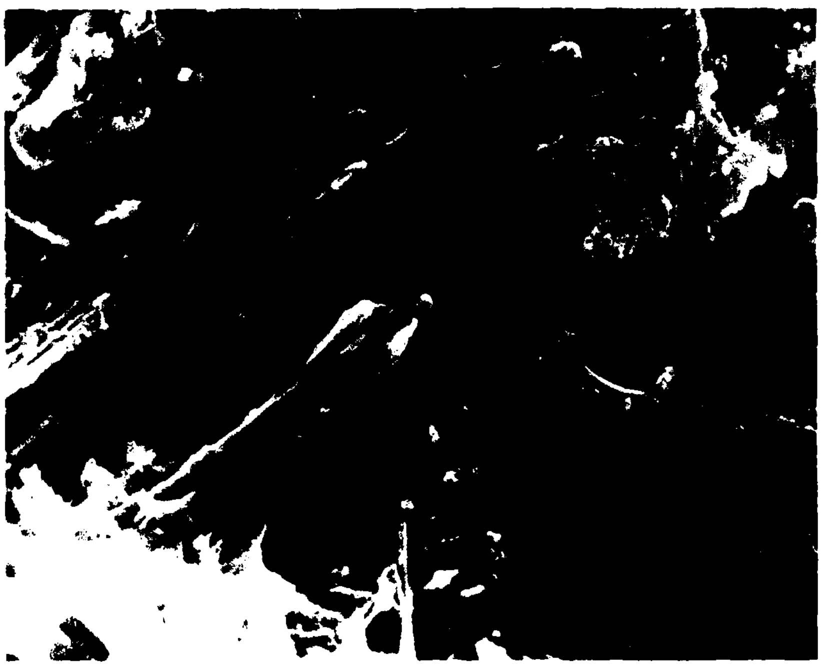
a. Micrograph 070284-13 of nonsalt concrete at 13-months age, X200. Dense C-S-H matrix surrounding residual cement grain (left) and fractured aggregate particle (right)



b. Micrograph 070284-8 of salt concrete at 13-months age, X200. Several air voids lined with ettringite needles

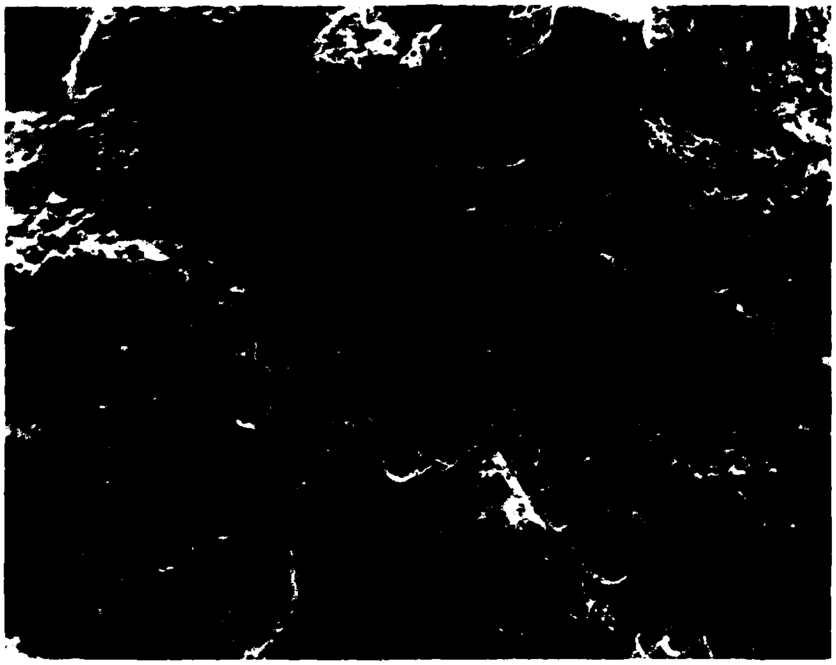
Figure 11

a. Micrograph 070284-15 of nonsalt concrete at 13-months age, X4750. Dense C-S-H matrix. Calcium hydroxide crystal in right center and probable residual cement grain in lower left

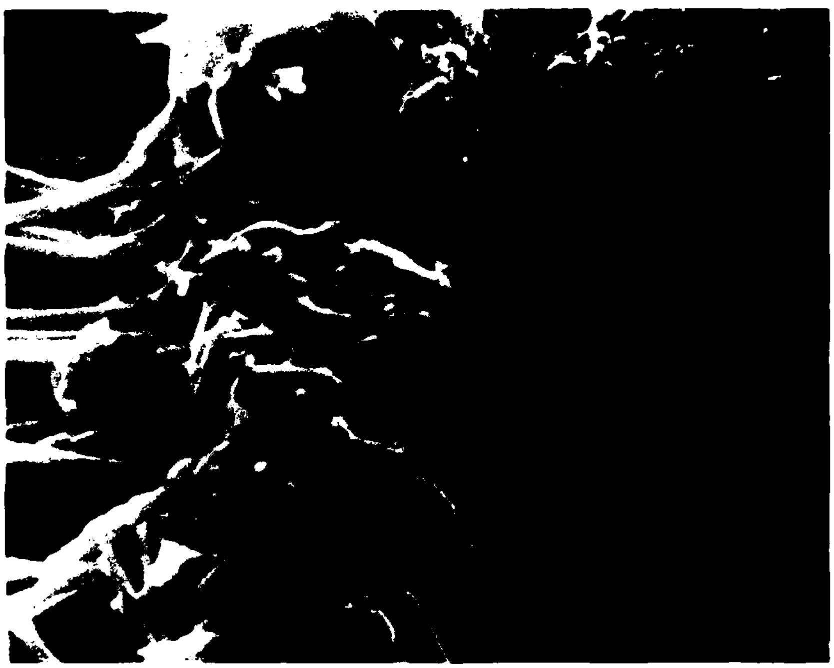


b. Micrograph 070284-9 of salt concrete at 13-months age, X5100. Probable ettringite laths at lower left, possible chloroaluminate at left, and dense C-S-H at right

Figure 12



a. Micrograph 090784-11 of salt concrete at 97-days age, X20. This shows the excessive air content of this concrete



b. Micrograph 070284-1 of salt concrete at 13-months age, X9300. Partially filled air void at left near fractured porous aggregate particle (right). Ettringite crystals in void on possible chloroaluminate

Figure 13

END

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